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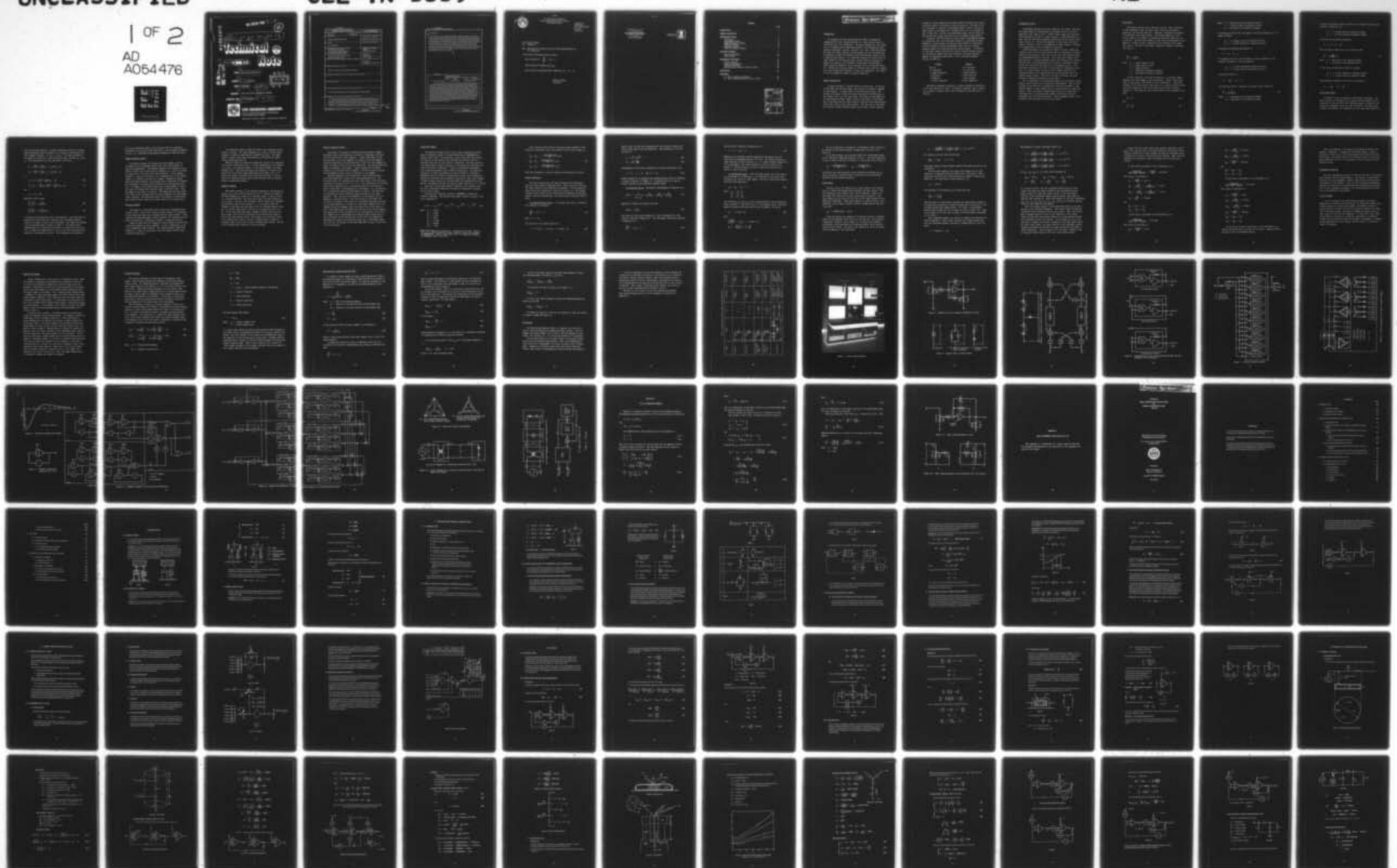

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of these modules are interconnected according to a signal flow diagram of the selected power system to form a simulated power system. If a simulated transient is injected into an input terminal of the simulated power system, different transient responses will appear on the terminals of each module simultaneously. These responses can be recorded for use in transient analysis. The output of each module can also be read through an output meter on the front panel. Besides the transient simulation, the PSS can be used for studying electrical steady-state problems at various AC frequencies. A definite advantage of the analog simulation is that voltages and currents can be recorded with meters or oscilloscopes at any point in the system.

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A power system simulator (PSS) that can be parametrically programmed to simulate the electrical transient performance of a medium-sized power system and its elemental components is described. It employs analog circuit modules to achieve simulation. Once programmed, the analog computer can be used to test the system for transients, load response, etc., by varying the parameters of the modules. The input and output terminals of these modules are interconnected according to a signal flow diagram of the selected power system to form a simulated power system. If a simulated transient is injected into an input terminal of the simulated power system, different transient responses will appear on the terminals of each module simultaneously. These responses can be recorded for use in transient analysis. The output of each module can also be read through an output meter on the front panel. Besides the transient simulation, the PSS can be used for studying electrical steady-state problems at various AC frequencies. A definite advantage of the analog simulation is that voltages and currents can be recorded with meters or oscilloscopes at any point in the system.

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From: Officer in Charge
To: Distribution

Subj: Errata Sheet for Technical Note N-1519, "Power System Simulator," by K. T. Huang, Ph D

1. Please make the following pen and ink corrections:

Page 12, Equation 12: $\frac{d^2y}{dt^2} + \omega^2 y = 0$

Page 14, Equation 23 (middle term): $\frac{1}{\omega}\phi_a$

Page 35, Figure 10 (far right hand edge - middle term): $\phi_b = E_c - E_a$

PETER D. TRIEM
By direction

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CONTENTS

INTRODUCTION

As equipped, the power system simulator (PSS) is designed for simulating electrical transient behavior in a power system rated up to 0.5 MVA with up to 20 transformers. The basic technique for this simulation is to employ analog computation methods to pre-program each power element (transformer, inductor, resistor, etc.) into a simulation module. The input and output terminals of these modules will be interconnected according to a signal flow diagram of the selected power system to form a simulated power system. If a simulated transient is injected into an input terminal of the simulated power system, different transient responses will appear on the terminals of each module simultaneously. These responses, therefore, can be recorded for use in transient analysis. Besides the transient simulation, PSS also can be used for studying electrical steady-state problems at various AC frequencies. The simulator can be equipped to double its present capability.

GENERAL DESCRIPTION

As shown in Figure 1, the PSS consists of three bays. On the top of the middle bay are three cages, each of which can contain a maximum of eight modules. A control panel is located directly below. The buttons on the panel control the operational modes of the PSS such as the compute, hold, set, and reset modes. The output of each module can be read through an output reader, located at the center of the middle bay, by pressing down the proper button in each row of the button matrix (lower left corner of the control panel). The lower part of the middle bay contains voltage reference modules that provide a stable reference

voltage for analog computation and buffer amplifier modules that provide a buffered output to recording or controlling devices. The bays on the left and right are identical; potentiometer panels, used to scale down input signals to the modules by a designed factor, are in the middle of each of these bays. Besides the potentiometer panel, each of these two bays contain four cages; each cage can also accommodate eight modules.

In general, the PSS consists of three kinds of programmable modules: (1) simulating, load, and transformer modules for simulating the power elements in a power system; (2) general analog modules for generating transient signals and simulating dynamic loads; and (3) a function generator module for simulating nonlinear analog signals. In addition to these basic modules, PSS also has several voltage reference modules for providing a standard reference voltage and two buffer amplifier modules for amplifying output power to drive recording equipment. Totally, the PSS has:

Modules	Modules
30 load	1 10-V reference
24 transformer	1 1-V reference
5 summer/integrator	1 100-mV reference
4 multiplier	1 10-mV reference
2 comparator	1 1-mV reference
1 function generator	2 buffer amplifier

The PSS was designed to operate at a center frequency of 60 Hz with a full-scale amplitude of ±10-V. The nominal frequency range of simulation is from 6 to 600 Hz, which can be exceeded but with some loss in accuracy.

PROGRAMMABLE MODULE

Programmable modules play a very important role in PSS. The input and output signals to these modules are designed in volts with their magnitude in the range of ±10 V. However these signals need not necessarily represent the input or output voltage of a simulated power element, they can represent any physical quantities such as current, power, speed, torque, etc. Because the magnitude of these input and output signals is limited to ±10 V, the magnitude of these signals is designed to be proportional to the real physical quantities.

Simulating modules are designed to simulate the most common power elements in the electrical power system such as transformers, resistors, inductors and capacitors; thus, they are the most useful modules among the programmable modules in the PSS. Since each power element can be represented by a standard mathematic module (the characteristic transfer function CTF), each simulating module is based on a mathematic module and has the same analog CTF built into its integrated circuit. The performance parameters of the CTF in each module are adjustable; therefore, if a power element's electrical CTF is known, the CTF of the simulating module can be adjusted to match the electrical CTF of the simulated power element. Once these two CTFs are matched, the power element is simulated analogically by the module.

Next in importance to the simulating modules are the general analog modules, which actually are conventional analog modules. They are more flexible in use and easier to program but require more modules to completely simulate a power element than are necessary with the simulating modules. Thus, the general analog modules are used for simulating a transient source or a special power element that has not been preprogrammed into the simulating modules. Each programmable module is described in the following sections of this report.

Load Module

This module consists of two identical circuits. Each circuit has its own independent input and output jacks, adjustable performance parameters, and overload indicator. Therefore, the module can simulate two individual loads simultaneously. The analog components of each circuit consists of a summer, an integrated operational amplifier, and an inverter. The CTF of this module is built into the integrated circuit amplifier. Figure 2 shows a simplified circuit diagram of this amplifier circuit. The CTF of this module, expressed in Laplace transformation form, is

$$\frac{e_o}{e_i} = \frac{-A}{B\,S + 1} \tag{1}$$

where e_o = output signal in volts

e_i = input signal in volts

S = Laplace operator

A = adjustable performance parameter

B = adjustable performance parameter

The CTF, expressed in the form of Equation 1, is the most common expression for load element in the power system. Figure 3 shows three kinds of load having a CTF similar to that of Equation 1. These load elements are (1) the resistor (Figure 3a), (2) a capacitor parallel with a resistor (Figure 3b), and (3) an inductor series with a resistor (Figure 3c). The electrical CTF of the resistor can be expressed in two ways,

$$\frac{V}{i} = R \tag{2}$$

and

$$\frac{i}{V} = \frac{1}{R} \tag{3}$$

where V = voltage across the simulated resistor

i = current through the simulated resistor

R = resistance of the simulated elements

For matching the CTF of the load module to the CTF of Equation 2, it is simple to define

e_o = V, voltage across the simulated resistor

e_i = i, current through the simulated resistor

and adjust the performance parameters to

$$A = -R; \quad B = 0$$

For matching the CTF of the load module to that of Equation 3, the variables in Equation 1 will be defined as

e_o = i, current through the simulated resistor

e_i = V, voltage across the simulated resistor

and adjust A and B to

$$A = -\frac{1}{R}; \quad B = 0$$

The electrical CTF of a capacitor in parallel with a resistor is

$$\frac{V}{i} = \frac{R}{R\,C\,S + 1} \tag{4}$$

where C = capacitance of the simulated element

R = resistance of the simulated element

so that the matching of these two CTFs can be obtained by defining the variables in Equation 1 as

e_o = V, voltage across the simulated element
e_i = i, current through the simulated element

and adjust the performance parameters

$$A = -A; \quad B = RC$$

The load shown in Figure 3b has its electrical CTF:

$$\frac{i}{V} = \frac{1/R}{(L/R)S + 1} \qquad (5)$$

where L = inductance of the simulated element
R = resistance of the simulated element

In this case, the matching of CTFs is to define

e_o = i, current through the simulated element
e_i = V, voltage across the simulated element

The performance parameters A and B will be adjusted to

$$A = -\frac{1}{R}; \quad B = \frac{L}{R}$$

Transformer Module

The module is used to simulate a single-phase transformer. The basic structure of the module is the same as the load module, but the difference is that the CTF of the transformer module is formed by combining two independent circuits of the load module. The module thus contains four summers, two integrated (circuit) operational amplifiers,

and two overload indicators. A typical equivalent circuit of a single-phase transformer, shown in Figure 4, is a two-port T-network with its four terminal variables: V_1, V_2, i_1, and i_2. The input variables of the module were chosen as V_1 and V_2; and the output variables as i_1 and i_2. The loop equations for this equivalent circuit are

$$V_1 = \left(\frac{L}{2} S + \frac{1}{2\,G}\right) i_1 + L_m S(i_1 + i_2)$$

$$V_2 = \left(\frac{L}{2} S + \frac{1}{2\,G}\right) i_2 + L_m S(i_1 + i_2)$$

or

$$V_1 - V_2 = \left(\frac{L}{2} S + \frac{1}{2\,G}\right) (i_1 - i_2) \qquad (6)$$

$$V_1 + V_2 = \left[\left(2\,L_m + \frac{L}{2}\right) S + \frac{1}{2\,G}\right] (i_1 + i_2) \qquad (7)$$

Let

$$L_t = L_m + \frac{L}{4}$$

Equations 6 and 7 become

$$\frac{i_1 - i_2}{V_1 - V_2} = \frac{2\,G}{G\,L\,S + 1} \qquad (8)$$

$$\frac{i_1 + i_2}{V_1 + V_2} = \frac{2\,G}{4\,G\,L_t\,S + 1} \qquad (9)$$

In comparing these Equations 8 and 9 with Equation 1, one finds that the equations are in the same form, therefore, the transformer module's structure is similar to that of the load module. The signal flow diagram of the transformer module is shown in Figure 5. The signals would sometimes have to be scaled down, scaled up, or inverted to avoid overload, to reduce the computing errors, and to take into consideration the operation of the amplifier circuits. The techniques for matching the

CTF of the transformer module to the electrical CTF of a simulated transformer are the same as those described in the preceding load module section; i.e., adjusting the performance parameters to match the CTFs.

Summer/Integrator Module

This module contains two integrators and two summers, each one containing its own independent circuit and, thus, being capable of operating independently. The feedback element in the integrator can be chosen as either one of three built-in elements; i.e., one of two different capacitors or a resistor with fixed resistance. If the feedback element is a capacitor, the device is an integrator; but if the feedback element is a resistor, the device is a summer. Besides the regular input and output terminals, the integrator has an additional IC terminal for the purpose of setting initial conditions in an integrating operation. The summer in this module sums up all incoming signals, inverts the sign, and transmits the resultant signal to the next stage. Thus, the summer can be used as an inverter. The summer has five input terminals, three 1-gain terminals and two 10-gain terminals, and four common output terminals. The operational mode of this module is controlled by mode control buttons located at the lower center of the control panel.

Multiplier Module

This module is a dual module which contains two independent multiplying circuits. Each of the circuits consists mainly of an integrated circuit block with three input terminals and one output terminal. Using different patching techniques to these terminals, the integrated circuit block can function as a multiplier, divider, or square-root device.

Figure 6a shows that the integrated circuit becomes a multiplier by connecting terminals e_z and e_o together. In this configuration e_x and e_y are independent input terminals. The resulting output signal from terminal e_o is equal to the product of the two signals from the input terminals divided by 10.

The connections shown in Figure 6b converts the integrated circuit block to a divider. The input terminals are e_z and e_x, and the output terminal is formed by connecting the terminals e_y and e_o. The output signal is equal to the signal from terminal e_z divided by the signal from e_x and multiplied by 10.

Figure 6c shows the connection diagram that converts the integrated circuit into a square-root device. In this configuration, the terminals e_x, e_y and e_o are combined together as the output terminal; the input terminal is e_z. The resulting signal from terminal e_o is equal to the square root of the input signal multiplied by the square root of 10. Because this module can perform three different functions, it is very useful for simulating certain special power elements such as induction motors or synchronous machines.

Comparator Module

This module consists of four identical comparators, each having two inputs, (V_{ref} and V_x) and two outputs (C and C). Because the signal at the input terminal V_{ref} serves as a reference signal, it must be fixed at a constant potential. The other input signal, fed into terminal V_x, can be varied. The sum of the voltages at the two inputs will determine the potential states of the outputs; i.e., if the sum of these two voltages is less than zero the output C will be the high potential state (or 5 V) and the other output C will be the low potential state (or 0 V). If the sum of these two input voltages is greater than zero, the first output C will be the low potential state and the other output C will be the high potential state. This change in the potential states of the outputs can be used to control an analog switch to connect or disconnect some circuits into or from a simulated power system. The CTF of the simulated power system will vary accordingly.

Function Generator Module

This module is designed for simulating nonlinear power elements. The method used in this simulation is similar to composing a nonlinear curve by using several linear segments. If the x-coordinates of the starting point of all line segments, the slopes of the line segments, and the y-coordinate of the starting point of the first line segment are known, the shape of this curve can be constructed. The function generator module is designed in this manner. Figure 7 shows that the module consists of 10 sections lined in sequence. The CTF of each section has been programmed in such a way as to represent a line segment.

The main components of this module are a selecting switch SW; a bias potentiometer ST; a diode; and a slope potentiometer SL. The selecting switch will determine the sign of the output of the section by switching to the position of "+x" or "-x." The x-coordinate of a starting point can be registered into a corresponding section by setting the input voltage equal to the magnitude of x-coordinate; i.e., by adjusting ST to a position at which the diode begins to conduct. Once the diode is conducting, ST and SL become the input resistance of the output amplifier. Thus, the gain of the amplifier (or the slope of the line segment) is controlled by SL. Since the sections in the module are activated in sequence as the value of x continuously increases, the gain of the output amplifier is a function of the slopes formed by the first through the nth line segment; thus, the registration of the slopes of those line segments into the module must also be in the correct sequence. The registration of the y-coordinate of the starting point of the first line segment can be accomplished by setting the input voltage equal to the x-coordinate of the starting point of the first line segment and adjusting the voltage of an additional input, y_{in}, of the output amplifier such that the voltage of the output amplifier is equal to the value of the y-coordinate.

SIMULATION EXAMPLE

The simulation example given in this report represents the actual power distribution system at the Naval Radio Station (NAVRADSTA(T)), Isabela, Puerto Rico. The transients at this station have been studied and reported in CEL Technical Note TN-1239* and therefore provide a convenient data base for the purpose of simulation. The power distribution system shown in Figure 8 consists of one substation transformer and three distribution transformers. These are three-phase transformers with Δ-connected primaries and y-connected secondaries. The name plate information of these transformers are shown in Figure 8. Because an underground cable is used for transmitting electrical power between the substation transformer and distribution transformers, the circuit diagram of Figure 8 shows capacitive coupling between the transmission line and ground. According to TN-1239, the value of these capacitors is C = 0.58 μF.

Total load of this power system is 400 kVA at an 0.8 power factor. The load is distributed among the distribution transformers in proportion to their ratings.

The electrical transients recorded at NAVRADSTA, Isabela were caused by lightning. The transient wave shape is shown in Figure 9, and can be expressed as

$$e_t(t) = a_1 t e^{-\alpha_1 t} + a_2 e^{-\alpha_1 t} + a_3 e^{-\alpha_2 t} + a_4 e^{-\alpha_3 t} \qquad (10)$$

where
$\alpha_1 = 0.3079$
$\alpha_2 = 0.7341$
$\alpha_3 = 0.2154$
$a_1 = 5.925$
$a_2 = -19.062$
$a_3 = 28.388$
$a_4 = -9.326$

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*Naval Civil Engineering Laboratory. Technical Note N-1239: Study of electrical power distribution system transients caused by lightning at NAVRADSTA(T), Isabela, Puerto Rico, by J. L. Brooks and K. Huang. Port Hueneme, Calif., Jun 1972.

This transient comes from the three-phase input terminals of the substation transformer, thus, the transient line-to-line voltages are

$$\begin{aligned} E_{at} - E_{bt} &= -\frac{(53)(2405)(6.8)}{35}\, e_t(t) \\ E_{bt} - E_{ct} &= \frac{(5)(2405)(6.8)}{35}\, e_t(t) \\ E_{ct} - E_{at} &= \frac{(48)(2405)(6.8)}{35}\, e_t(t) \end{aligned} \tag{11}$$

With this information, the power system can be simulated as follows.

Sources Simulation

The sources which excite the power system are the 60-Hz power source and the transient lightning source. These sources are fed into the input terminals of the substation transformer. In this simulation these sources are considered as infinitive sources; i.e., the voltage waveform of the sources are not affected by the impedance of the power system. With this consideration, each source may be evaluated individually.

(1) Sinusoidal Power Source. To simulate this source, a differential equation is introduced.

$$\frac{dy^2}{dt^2} + \omega^2 y = 0 \tag{12}$$

where $\omega = 377$

The solution of this simple equation is

$$y = A \sin \omega t + B \cos \omega t = C \sin(\omega t + \theta) \tag{13}$$

where A and B are arbitrary constants which can be used to control the initial phase angle θ and the amplitude C. The expressions of C and θ are given as

$$C = (A^2 + B^2)^{1/2} \tag{14}$$

$$\theta = \tan^{-1}\left(\frac{B}{A}\right) \tag{15}$$

From Equation 13 the initial conditions of y and its derivative y are

$$t = 0, \quad y = B \quad \text{and} \quad \dot{y} = A\,\omega \tag{16}$$

Based on Equations 12 through 16 the sinusoidal power source is simulated as shown in Section 1 of Figure 10. A scaling factor K_1 is used to prevent overload of the simulated sinusoidal source.

<u>(2) Transient Source</u>. The Laplace transformation of Equation 10 is

$$E_t(S) = \frac{a_1}{(S + \alpha_1)^2} + \frac{a_2}{S + \alpha_1} + \frac{a_3}{S + \alpha_2} + \frac{a_4}{S + \alpha_3} \tag{17}$$

Equation 17 consists of terms in the form

$$E_\alpha(S) = \frac{a}{S + \alpha} \tag{18}$$

Note that the first term of Equation 17 can be considered to be the square of the form of Equation 18. The time domain differential equation of Equation 18 is

$$\frac{de_\alpha}{dt} + \alpha\, e_\alpha = 0 \tag{19}$$

and the initial condition of Equation 18 is

$$t = 0, \quad e_\alpha = 0 \tag{20}$$

Therefore, the transient waveform expressed in the equation can be simulated by programming Equations 19 and 20. The analog simulation of these equations is given in Figure 11. In a similar fashion, Equation 17 can be programmed. The analog simulation is given in Section 2 of Figure 10. Scaling factor K_2 is used to prevent the analog circuit Section 2 from an overload.

(3) Three-Phase Source. Since the high voltage side of the substation transformer is Δ-connected, it is convenient to use line-to-line voltage ϕ_a, ϕ_b, and ϕ_c as input signals. The sum of these three signals, therefore, must equal zero

$$\phi_a + \phi_b + \phi_c = 0 \tag{21}$$

where
$$\phi_a = E_b - E_c$$
$$\phi_b = E_c - E_a$$
$$\phi_c = E_a - E_b$$

The voltages E_a, E_b, and E_c are the voltages between line and ground, as shown in Figure 8. The 60-Hz source is a three-phase source, each phase angularly displaced 120 deg from the other two phases. Let ϕ_a be

$$\phi_a = C \sin(\omega t + \theta) \tag{22}$$

then

$$\frac{1}{\omega}\left(\frac{d\phi_a}{dt}\right) = \frac{1}{\omega}\dot{\phi}_a = C \cos(\omega t + \theta)$$

$$\phi_b = -\left(\frac{\sqrt{3}}{2\,\omega}\dot{\phi}_a + \frac{1}{2}\ \phi_a\right) \tag{23}$$

By use of Equations 21 through 23, a three-phase, 60-Hz voltage can be obtained by the analog schematic diagram shown in Section 3 of Figure 10.

In a similar manner, the transient signal for a three-phase system can be simulated by employing Equations 11 and 21. The analog simulation of this is shown in Section 3 of Figure 10. The values of β_1 and β_2 are

$$\beta_1 = \frac{(48)(2405)(6.8)}{35}; \quad \beta_2 = \frac{(5)(2405)(6.8)}{35}$$

The line-to-line input potential of the substation transformer ϕ_a, ϕ_b, and ϕ_c represents a potential which is the sum of the AC sinusoidal potential and the transient potential.

Power System

The main task in the simulation of a power system is the construction of a signal flow diagram which represents the power system. From this diagram an actual analog circuit can be connected. Figure 12 is the signal flow diagram of the power system shown in Figure 8. The input signals ϕ_a, ϕ_b, and ϕ_c are the line-to-line input voltages of the substation transformer. These input signals are simulated from a source simulation circuit shown in Figure 10 and are stepped down by the ratio $1/n_S$, where

$$n_S = 38{,}000/2{,}400 = 15.83$$

Since the sources are assumed to be infinitive sources, a feedback signal to the simulated source circuit is not required. The substation transformer, therefore, can be simply represented by three identical load modules, each consisting of an inductance module and an inductor series resistor module. The value of the inductor L_o can be calculated from the nameplate of the transformer

$$L_o = \frac{2,400^2}{3,200,000}(3)\left(\frac{67}{1,000}\right)\left(\frac{1}{377}\right) = 9.6 \times 10^{-4} \text{ H}$$

The resistor R_o can be selected such that

$$|R_o| << |\omega|, \quad \omega = 377$$

The output signals of these modules represent the output currents of the transformer.

The next power element on the signal flow diagram will be three *capacitors, Y-connected across the power* lines to the ground. Three capacitors paralleled with resistor modules are needed to simulate the capacitors. The capacitance of these modules C_o are

$$C_o = 0.58 \ \mu F$$

and resistance of the modules R_o are chosen such that

$$|R_o| >> \left|\frac{1}{C\ \omega}\right|$$

When the output of these modules represent the output phase voltages of the substation transformer, the phase voltages must be converted to line voltages through three summer modules. The vector's relationships between phase voltages and line voltages are shown in Figure 13a. These line voltages will be the input voltages of the three-phase transformers T_1, T_2, and T_3.

Nine transformer modules are required to complete the simulation of these transformers. Before these converted line voltage signals feed into the transformer modules, they must be stepped down by a ratio 1/n where

$$n = 4,160/120 = 34.7$$

The parameters of these transformer modules are

$$L_1 = \frac{120^2}{150,000}(3)\left(\frac{26}{1,000}\right)\left(\frac{1}{377}\right) = 2 \times 10^{-5}\ \mathrm{H}$$

$$L_2 = \frac{120^2}{500,000}(3)\left(\frac{48}{1,000}\right)\left(\frac{1}{377}\right) = 1.0 \times 10^{-5}\ \mathrm{H}$$

$$L_3 = \frac{120^2}{225,000}(3)\left(\frac{31}{1,000}\right)\left(\frac{1}{377}\right) = 1.6 \times 10^{-5}\ \mathrm{H}$$

and L_{m1}, L_{m2}, L_{m3}, G_1, G_2 and G_3 can be estimated as

$$L_{m1} = 300\ L_1, \qquad L_{m2} = 300\ L_2, \qquad L_{m3} = 300\ L_3$$

$$G_1 = \frac{10}{L_1\ \omega}, \qquad G_2 = \frac{10}{L_2\ \omega}, \qquad G_3 = \frac{10}{L_3\ \omega}$$

It is noted in Table 1 that the transformer modules have two input signals (the input and output voltages of the transformer) and two output signals (the input and output currents of the transformer). Therefore, these transformer modules require another input signal to complete input information. These input signals for the nine transformers (V_{a1}, V_{a2}, V_{a3}, V_{b1}, V_{b2}, V_{b3}, V_{c1}, V_{c2}, and V_{c3}) are feedback from the outputs of the respective load modules.

One of the output signals of each transformer module is the input current of the simulated transformer. This current passes through the transformer and is different from the line current. Thus, this current must be stepped down by a ratio 1/n and converted to line current. Figure 13b shows the relationship between the currents passing through the transformer and the line currents. Line currents I'_a, I'_b, I'_c will feed back to complete the current information of the whole power system. The other output signal, the output current of the transformer, passes through load modules and provides the output voltage for each phase of these transformers. These voltages will be the load's response to the AC sinusoidal input sources as well as to any transient inputs.

Because the total load of this power system is 400 kVA at an 0.8 power factor and the load is distributed among the distribution transformers in proportion to their ratings, the load for each phase can be considered as a resistor in parallel with an inductor. Thus, the load connected to each phase of these transformers can be calculated as follows:

(1) The load on each phase of the transformer T_1 is

$$\frac{(400)(150)}{(150 + 500 + 225)(3)} = \frac{20,000}{875} = 22.86 \text{ kVA}$$

The current in each phase is

$$I_{a1} = \frac{22.86}{120} = 190.5 \text{ A}$$

$$R_{a1} = \frac{120}{0.8\ I_{a1}} = \frac{120}{0.8(190.5)} = 0.787\ \Omega$$

$$\omega L_{a1} = \frac{120}{0.6\ I_{a1}} = \frac{120}{0.6(190.5)} = 1.05\ \Omega$$

$$L_{a1} = \frac{1.05}{377} = 2.785 \text{ mH}$$

and

$$R_{a1} = R_{b1} = R_{c1}$$

$$L_{a1} = L_{b2} = L_{b3}$$

(2) The load on each phase of the transformer T_2 is

$$\frac{(400)(500)}{(150 + 500 + 225)(3)} = 76.19 \text{ kVA}$$

The current in each phase is

$$I_{a2} = \frac{79,190}{120} = 635 \text{ A}$$

$$R_{a2} = \frac{120}{0.8\ I_{a2}} = 0.236\ \Omega$$

$$\omega L_{a2} = \frac{120}{0.6\ I_{a2}} = 0.315\ \Omega$$

$$L_{a2} = \frac{0.315}{377} = 0.835\ \text{mH}$$

and

$$R_{a2} = R_{b2} = R_{c2}$$

$$L_{a2} = L_{b2} = L_{c2}$$

(3) The load on each phase of the transformer T_3 is

$$\frac{(400)(225)}{(150 + 500 + 225)(3)} = 34.28\ \text{kVA}$$

The current in each phase is

$$I_{a3} = \frac{34,280}{120} = 286\ \text{A}$$

$$R_{a3} = \frac{120}{0.8\ I_{a3}} = 0.524\ \Omega$$

$$\omega L_{a3} = \frac{120}{0.6\ I_{a3}} = 0.699\ \Omega$$

$$L_{a3} = \frac{0.699}{377} = 1.855\ \text{mH}$$

$$R_{a3} = R_{b3} = R_{c3}$$

$$L_{a3} = L_{b3} = L_{c3}$$

(4) All chosen values of resistances in the load module of an inductor paralleled with a resistor are very small, compared with the reactance of the corresponding inductor.

After all parameters in the signal flow diagram are defined, the diagram is completed. To program the whole power system, it may be necessary to scale down or scale up the signal which flows in the simulated system. The scaling factor will be chosen in such a way that the signal magnitude will be in a range between 1 and 9 V, which will give maximum accuracy.

PROGRAMMING TECHNIQUES

The basic programming techniques for PSS are the same as the programming techniques for the analog computer. PSS consists of many modules which have been preprogrammed to simulate special power elements such as transformers or load elements. Thus, to avoid unnecessary programming mistakes and confusion on the interconnections of modules and the adjustment of their performance parameters, the following guidelines provide aid in the handling of these modules.

Circuit Diagram

A circuit diagram of the simulated power system is of primary importance for accurate simulation because all connections between power element modules are based on this diagram. The diagram, therefore, should indicate all values of electrical parameters required for simulation of the power system. Some circuit diagrams give these values in ohms, others in "pu" (per unit impedance). In the latter cases, these values should be converted to resistance, capacitance, or inductance because this conversion will make all parameters independent of frequency. Having completed the circuit diagram, the next step is to construct a signal flow diagram.

Signal Flow Diagram

A power element has at least one pair of terminals or ports. When the element is energized, two parameters can be measured at each port: (1) the current through the terminal and (2) the voltage across the terminals. Theoretically, either one of these parameters can be designated as the input signal of a power element module, making the other the output signal of the module. Once a simulated power element module is designed, its input and output signals are fixed, and the other power element modules connected to this module must have the output signal of this module as their input signal. In this manner, and consistent with the circuit diagram of the simulated power system, a signal flow diagram can be constructed. In the example in this report, the input and output signals of the load and transformer modules were preassigned and are listed in Table 1.

In certain cases, however, a difficulty arises in constructing a signal flow diagram in the prescribed manner. For example, consider the transformer with its secondary connected to a load consisting of a series combination of an inductor and resistor as shown in Figure 14a. According to Table 1, the output signal of the secondary of the transformer module is output current i_2, while the input signal of the load module is input voltage V. Because these two signals are different in physical units, the output terminals of the transformer module cannot be directly connected to the input terminals of the load module. To overcome this difficulty, a dummy element must be inserted between these two elements. The dummy element is a resistor of relatively high resistance and is placed across the secondary of the transformer. The value of resistance must be so chosen as to have only a negligible effect on the simulated circuit when connected. Figure 14b is the circuit diagram with the resistor connected. Figure 14c, then, is the signal flow diagram of the circuit in Figure 14b. Thus, the dummy element serves its purpose—to complete the signal flow diagram.

Scaling Techniques

Two scaling techniques are often used for programming a power system. These scaling techniques are magnitude scaling and frequency (time) scaling. All simulating modules in PSS must be designed with their output signals in the range of 1 to 10 V to provide the most accurate results. Magnitude scaling techniques will scale down a large signal to the proper range of magnitude by use of a potentiometer and by scaling up a small signal by adjustment of the feedback resistor R_f in the operational amplifier of the module. In each case of scaling the signal down or up, the scaling factors must be recorded in order that the real magnitude of the output signal can be determined.

PSS is designed to operate at a center frequency of 60 Hz with a nominal frequency range of 6 to 600 Hz. The simulation of high frequency response of a power system beyond 600 Hz will result in decreased accuracy. In order to overcome this defect a frequency scaling technique can be employed. The technique is to replace the high frequency source with a source whose frequency falls within the nominal frequency range of the modules, and to scale all values of inductances, capacitances and frequencies as indicated by Equations 24 and 25:

$$L_o \omega_o = L_o \omega_N \frac{\omega_o}{\omega_N} = (L_o f_N)\left(2\pi \frac{f_o}{f_N}\right) = L\,\omega \qquad (24)$$

$$\frac{1}{C_o\,\omega_o} = \frac{1}{C_o\,\omega_N \frac{\omega_o}{\omega_N}} = \frac{1}{C_o f_N \left(2\pi \frac{f_o}{f_N}\right)} = \frac{1}{C\,\omega} \qquad (25)$$

where f_o = original high frequency

f_N = frequency scaling factor

$$\omega_o = 2\pi f_o$$

$$\omega_N = 2\pi f_N$$

$$\omega = 2\pi f$$

$f = f_o/f_N$ = scaled frequency (between 6 and 600 Hz)

L_o = original inductance

L = scaled inductance

C_o = original capacitance

C = scaled capacitance

The time response then becomes

$$t = f_N\, t_o \tag{26}$$

where t_o = original response time
t = scaled response time

If a linear power system has several exciting sources whose frequencies are widely varied, the superposition theory can be used to simulate this system. The total response of the system can be determined by summing the responses of each exciting source acting alone. Frequency scaling techniques may be required to let the exciting frequency fall within the nominal frequency range. Then, by use of Equation 26 to convert all output signal waveforms to the original time base, the total response in the original time base can be determined.

Characteristic Transfer Function (CTF)

To simulate a power element by using a simulating module of PSS as previously mentioned, it is necessary to match the CTF of the module to the electrical CTF of the power element. As indicated by Figure A-1 and Equation A-11 in Appendix A, the CTF of the simulating module can be expressed as

$$\phi = \frac{-\frac{k_f}{k_i}}{k_f\ C\ S + 1} = \frac{-A}{B\ S + 1} \tag{27}$$

where ϕ = CTF of the simulating module

k_i = function of the wiper position on potentiometer ΔR_i

k_f = function of the wiper position on potentiometer ΔR_f

$$A = \frac{k_f}{k_i} \tag{28}$$

$$B = k_f\ C \tag{29}$$

If the electrical CTF of the power element to be simulated is

$$X = \frac{A'}{B'\ S + 1} \tag{30}$$

where X is the electrical CTF of the power element, then A' and B' are known constants.

To adjust the values of k_i and k_f in Equations 28 and 29, the positions of the wipers of potentiometers ΔR_i and ΔR_f are adjusted such that

$$\frac{k_f}{k_i} = A = A' \tag{31}$$

$$k_f C = B = B' \tag{32}$$

Then the simulating module is analogically identical to the simulated power element. The difference in sign between the CTF in Equations 27 and 30 is not significant since the change in sign of ϕ can easily be accomplished by using an inverter.

In the PSS, however, there is no indication of the values of k_i and k_f; therefore, the calibration of k_i and k_f to satisfy Equations 31 and 32 is rather difficult. Fortunately, this difficulty can be overcome by checking the CTFs in Equations 27 and 30 with VHF signals and with DC signals, respectively. For VHF signals,

$$\phi\Big|_{f>>1} = -\frac{1}{C\,k_i\,S} = -\frac{A}{B\,S} \tag{33}$$

$$X\Big|_{f>>1} = \frac{A'}{B'\,S} \tag{34}$$

For DC signals,

$$\phi\Big|_{f=0} = -\frac{k_f}{k_i} = A \tag{35}$$

$$X\Big|_{f=0} = A' \tag{36}$$

From Equations 33 through 36, it is not difficult to determine a procedure for matching the two CTFs by using the procedure:

(1) Calculate the value of $|X|_{f>>1}$ for a fixed high frequency f; i.e.,

$$|X|_{f>>1} = \frac{A'}{B'\,\omega}\,; \qquad \omega = 2\pi f$$

where A', B', and ω are known values.

(2) Use a unit input signal at the fixed high frequency to excite the simulating module and adjust k_i such that

$$\left|\phi\right|_{f>>1} = \left|X\right|_{f>>1} = \frac{A'}{B'\ \omega}$$

(3) Calculate the value of $\left|X\right|_{f=0}$ at DC signal, i.e.,

$$\left|X\right|_{f=0} = A'$$

(4) Use a unit input DC signal to excite the simulating module and adjust k_f such that

$$\left|\phi\right|_{f=0} = \left|X\right|_{f=0} = A'$$

(5) Check the sign of ϕ, if ϕ and χ are opposite in sign, an inverter is needed to change the sign of ϕ.

CONCLUSIONS

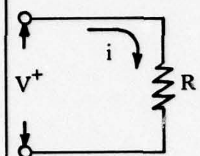
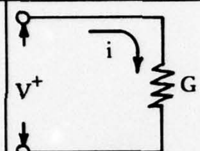
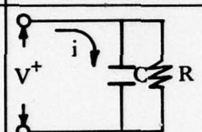
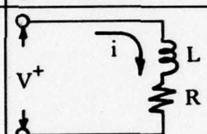
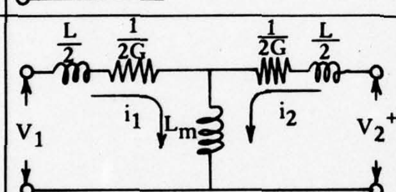
The Power System Simulator (PSS) is a powerful tool that can be used to represent analogically medium-sized power systems. Once programmed, the analog computer can be used to test the systems for transients, load response, etc., by varying the parameters of the modules.

On the analog simulation, the power system is represented analogically by various hardware system modules. Thus, once programmed the latter need not be reprogrammed, as would be necessary with a software model. Expansion of the power system would only require additional modules, again without reprogramming the existing analog representation.

A definite advantage of the analog simulation is that voltages and currents can be recorded with meters or oscilloscopes at any location in the system. Unlike a digital computer, where each parameter must be explicitly specified to obtain a measurement, waveforms can be recorded on an analog simulation by moving the oscilloscope probe to the location in question. Thus, signal tracing and system response can be done as easily as normal troubleshooting of hardware circuits.

The PSS can also be used to solve other engineering problems. Basic engineering applications of this equipment are described in Appendix B.

Table 1. List of Assigned Input and Output Signals for Programmable Modules

Module	Symbol	CTF	Input Signal	Output Signal
Resistor (R)		$\frac{\nu}{i} = R$	i = current through R	ν = voltage across R
Conductor (G)		$\frac{i}{\nu} = G = \frac{1}{R}$	ν = voltage across G	i = current through G
Capacitor parallel with resistor (C || R)		$\frac{\nu}{i} = \frac{R}{RCS + 1}$	i = total current through the network	ν = voltage across the network
Inductor series with resistor (L + R)		$\frac{i}{\nu} = \frac{\frac{1}{R}}{\frac{L}{R}S + 1}$	ν = voltage across the network	i = current through the network
Transformer (T)		$\frac{i_1 - i_2}{V_1 - V_2} = \frac{2G}{GLS + 1}$ $\frac{i_1 + i_2}{V_1 + V_2} = \frac{2G}{4GL_tS + 1}$	V_1 = voltage across the primary of the transformer V_2 = voltage across the secondary of the transformer	i_1 = current through the primary winding i_2 = current through the secondary winding

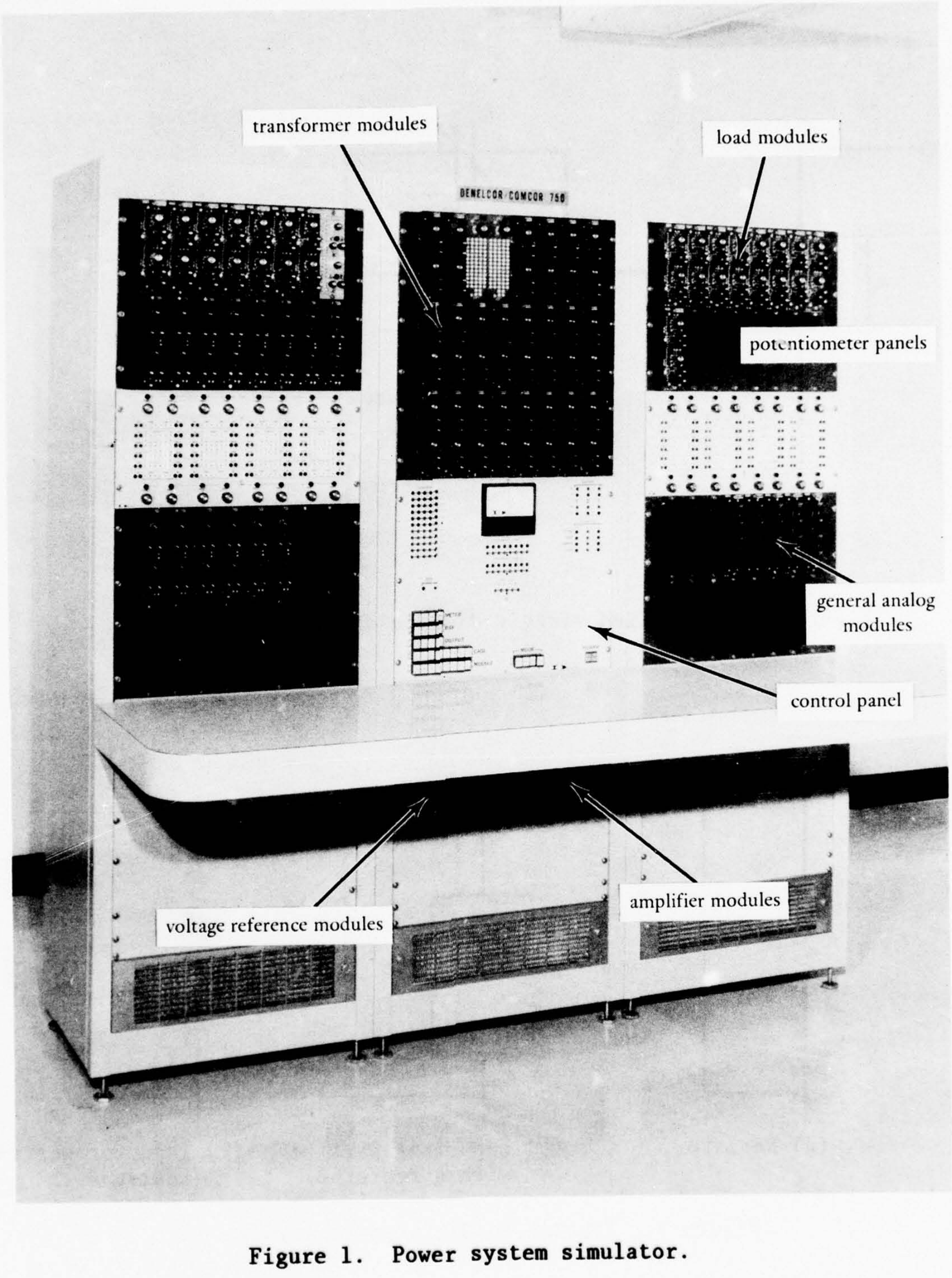


Figure 1. Power system simulator.

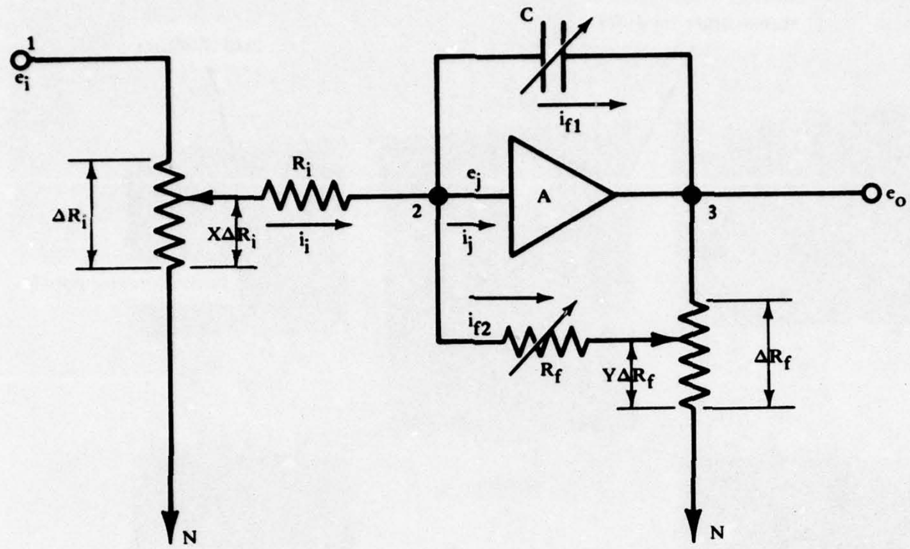
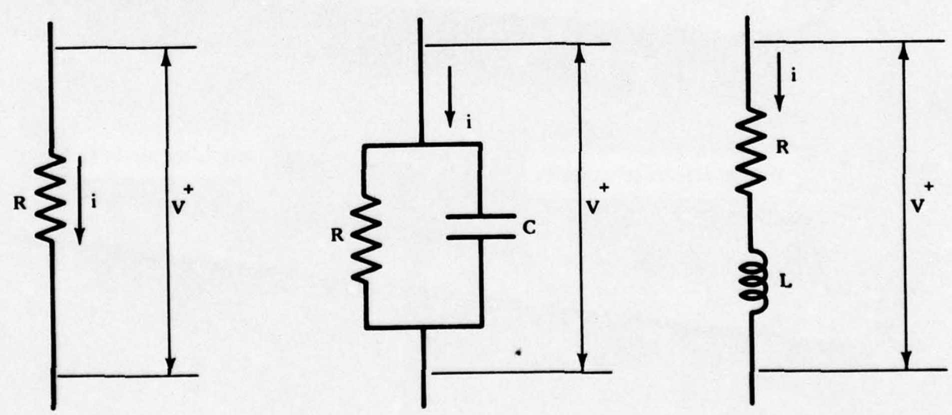


Figure 2. Simplified circuit diagram of amplifier circuit.



(a) Resistor.

(b) Capacitor parallel with a resistor.

(c) Inductor series resistor.

Figure 3. Typical loads in power system.

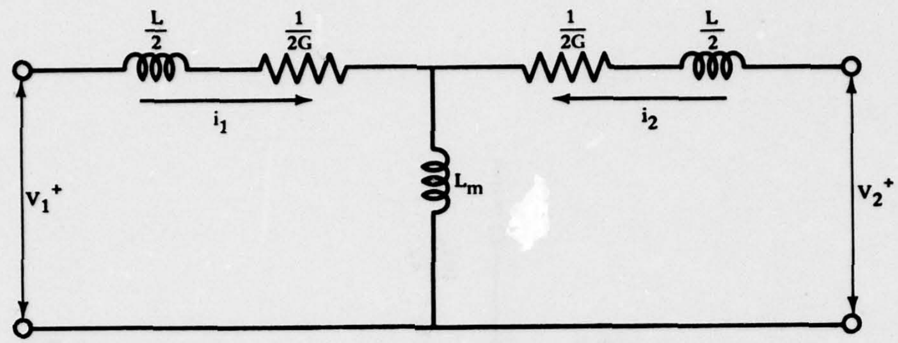


Figure 4. Equivalent circuit of a single phase transformer.

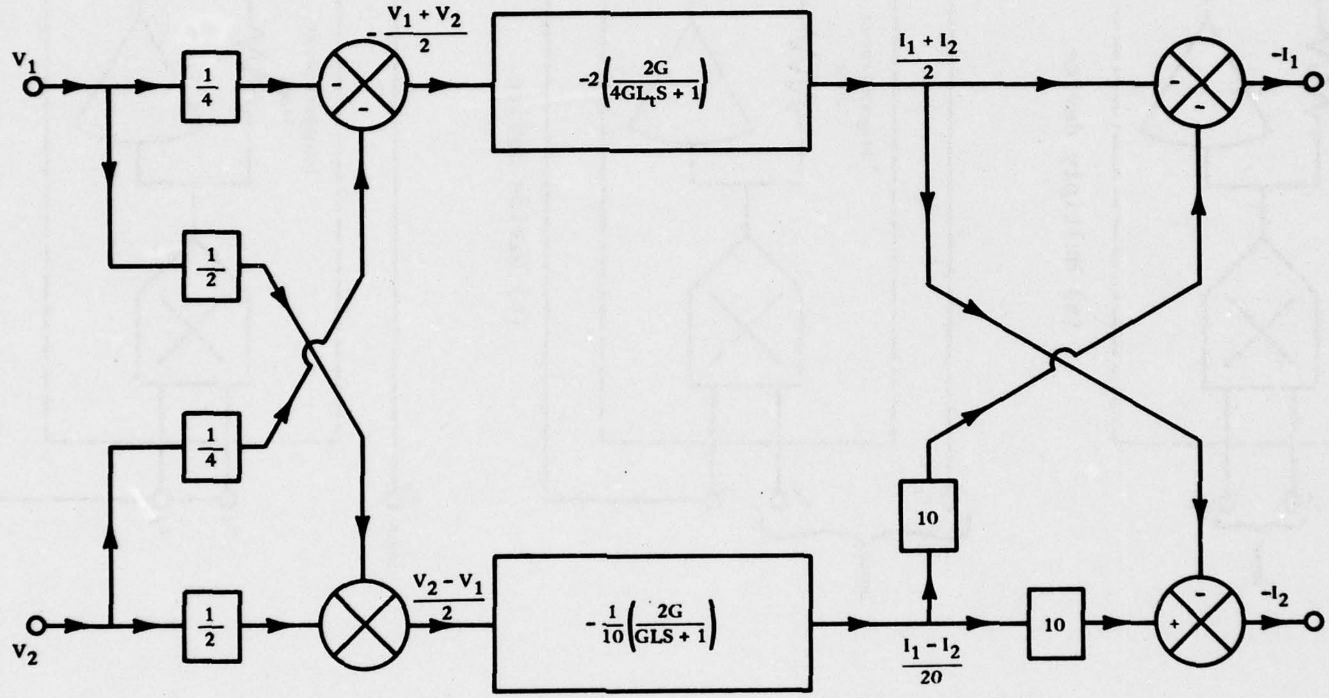
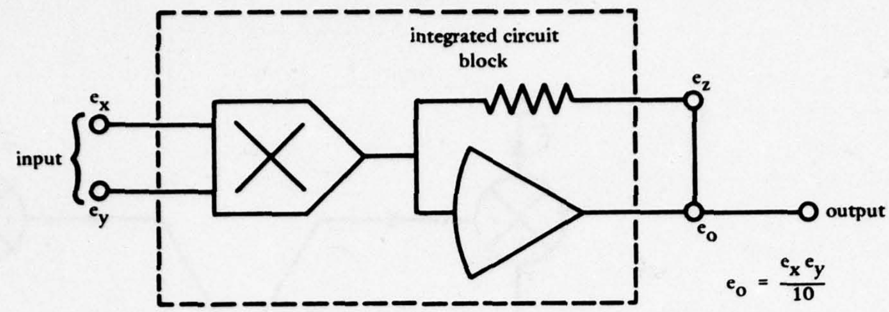
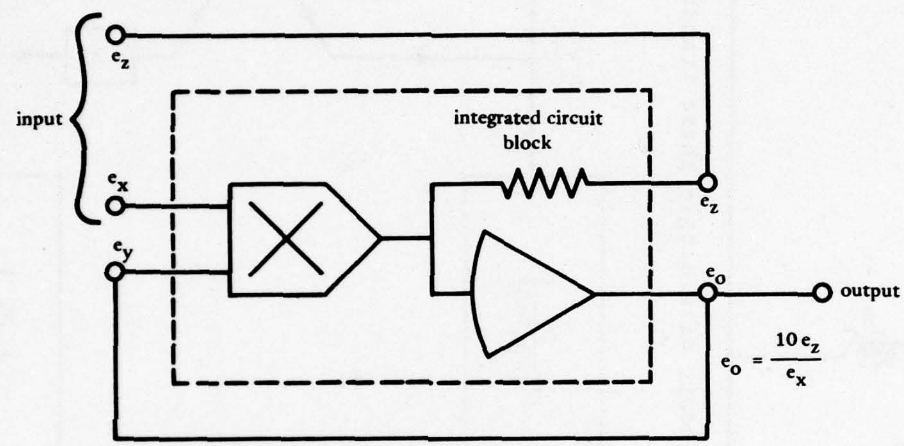


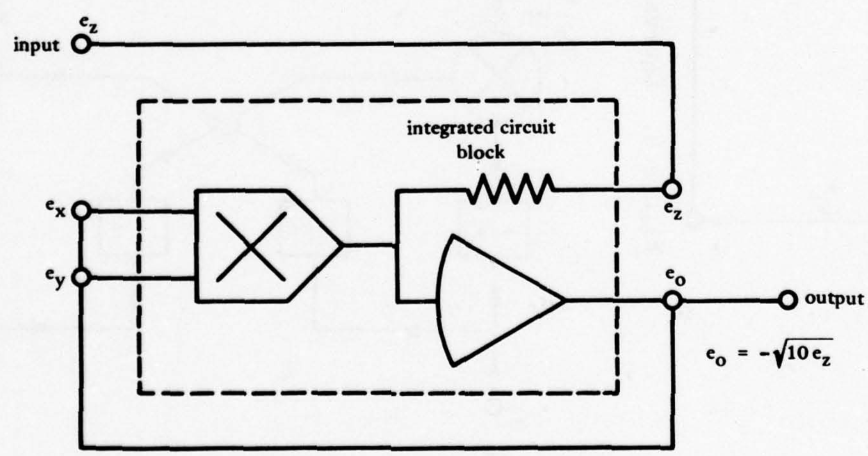
Figure 5. Signal flow diagram of a transformer module.



(a) Multiply device.



(b) Divide device.



(c) Square-root device.

Figure 6. Configurations of the interconnections between the four terminals of the multiplier.

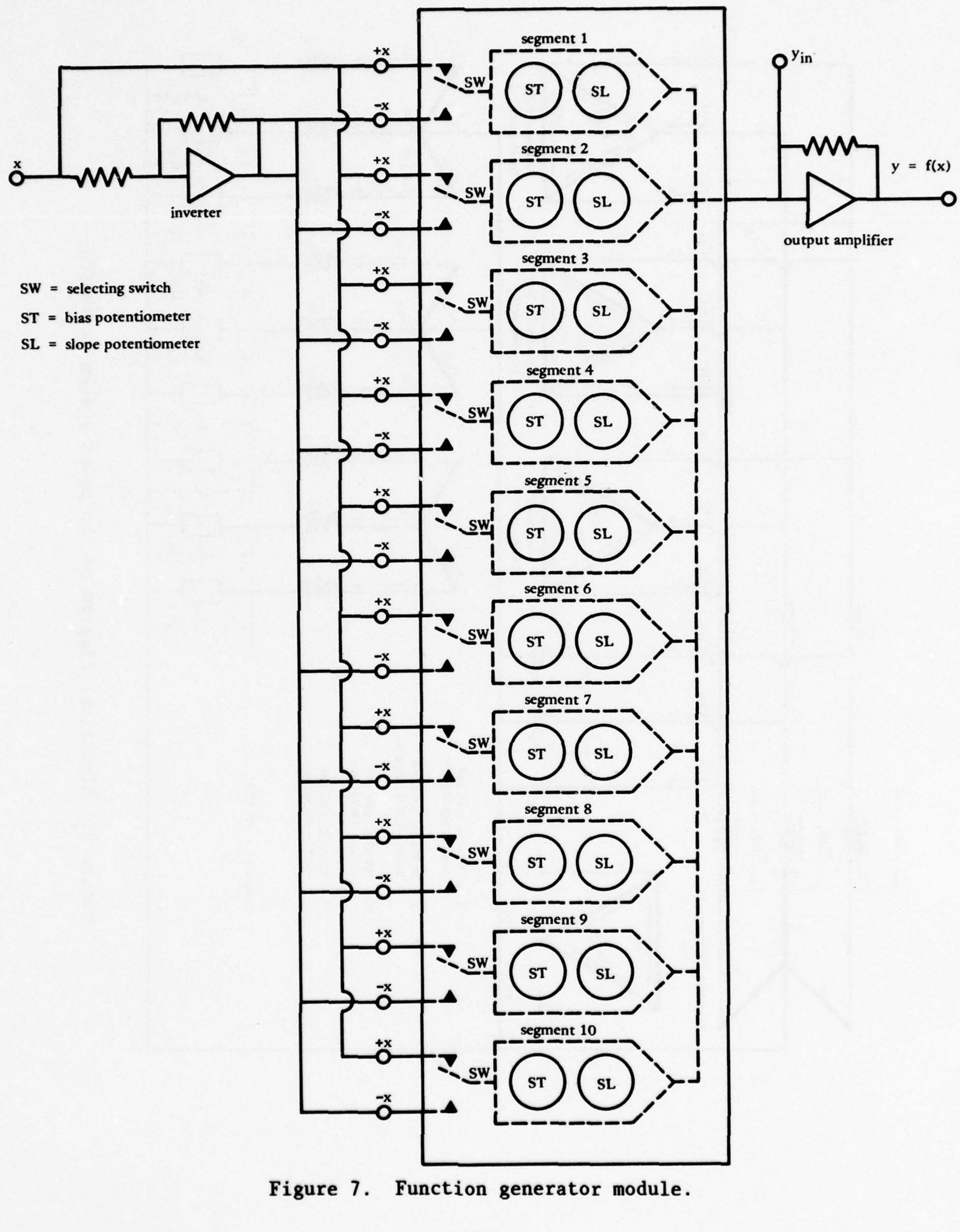


Figure 7. Function generator module.

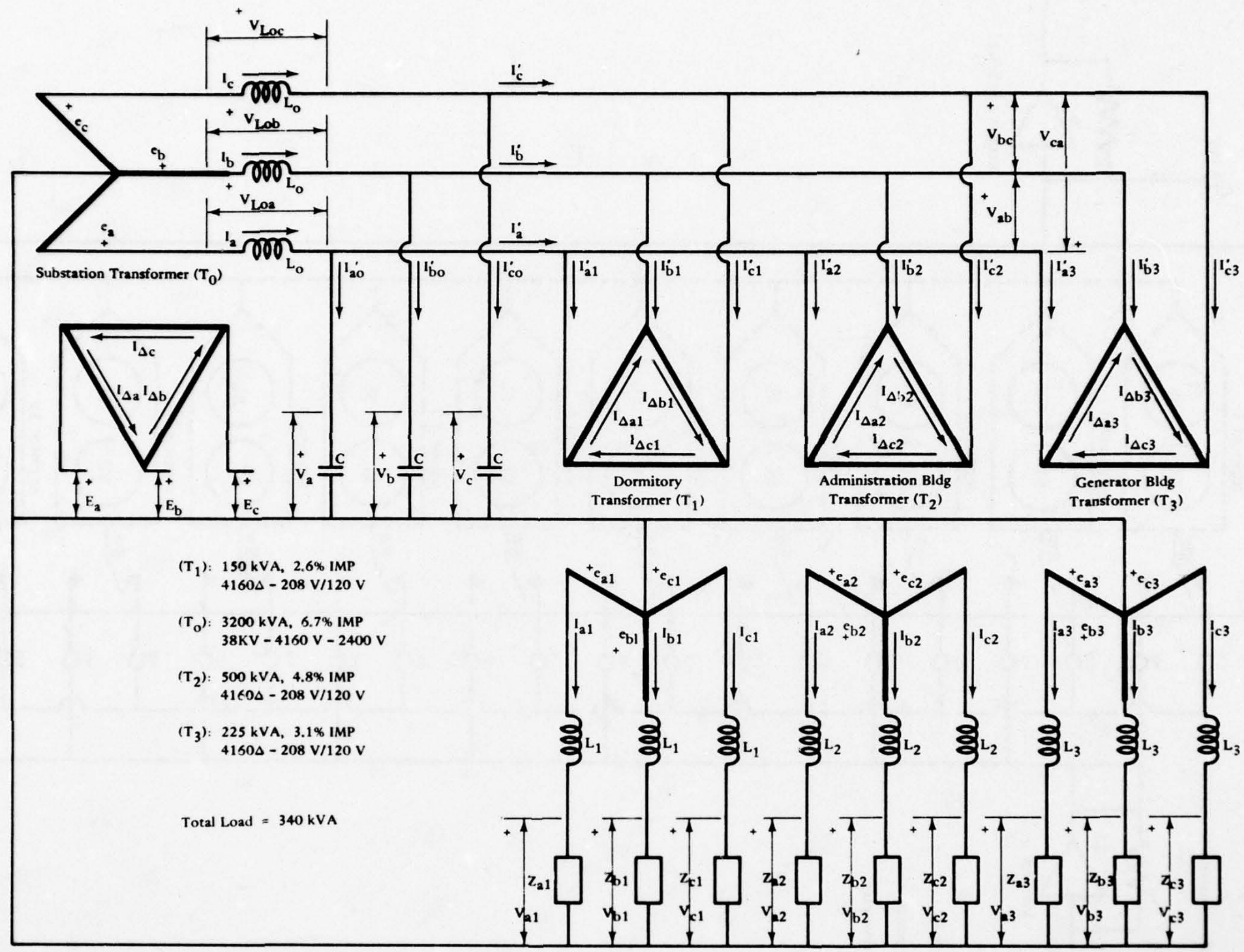


Figure 8. Electrical diagram of the power system at NRS(T).

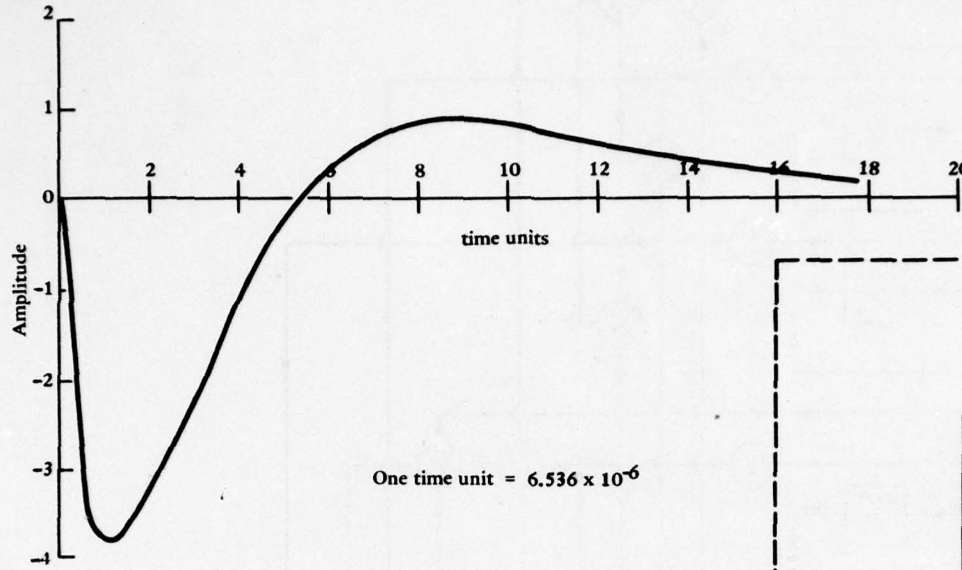


Figure 9. Calculated transient wave shape.

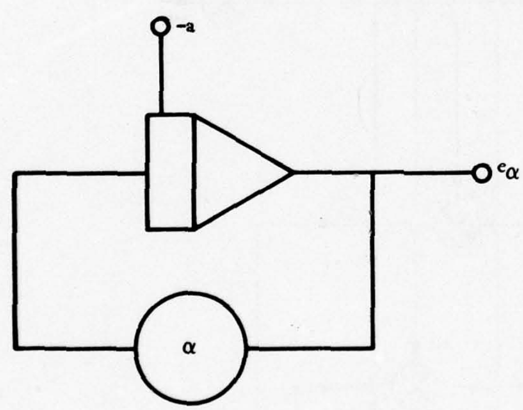


Figure 11. Schematic diagram of simulation $e_d = ae^{-\alpha t}$.

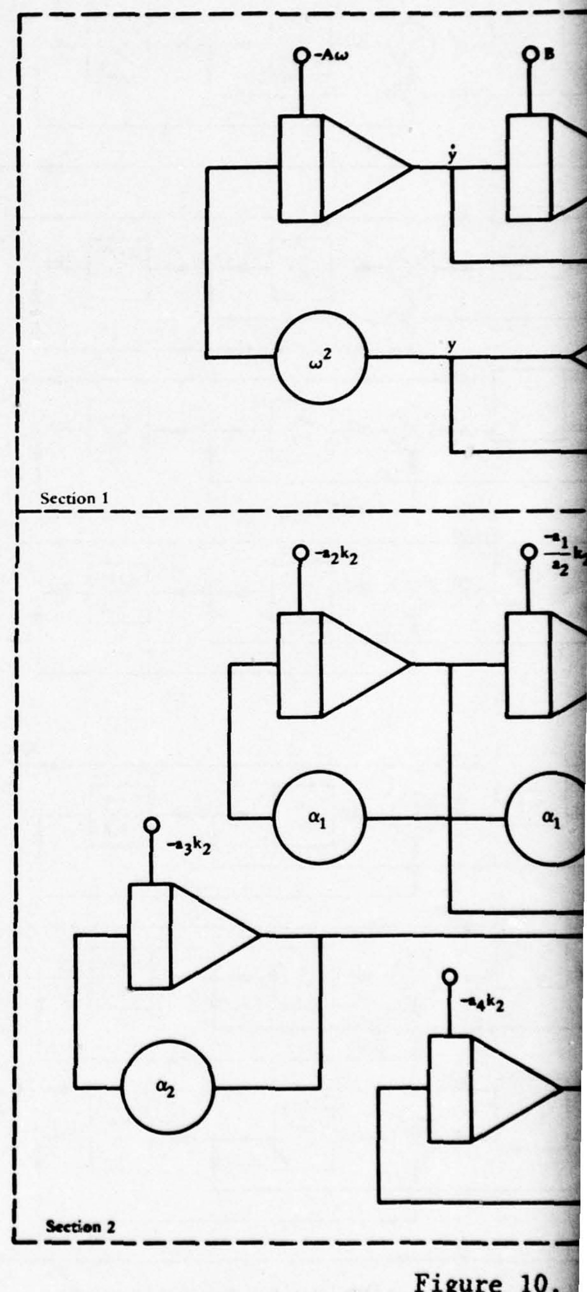


Figure 10.

2

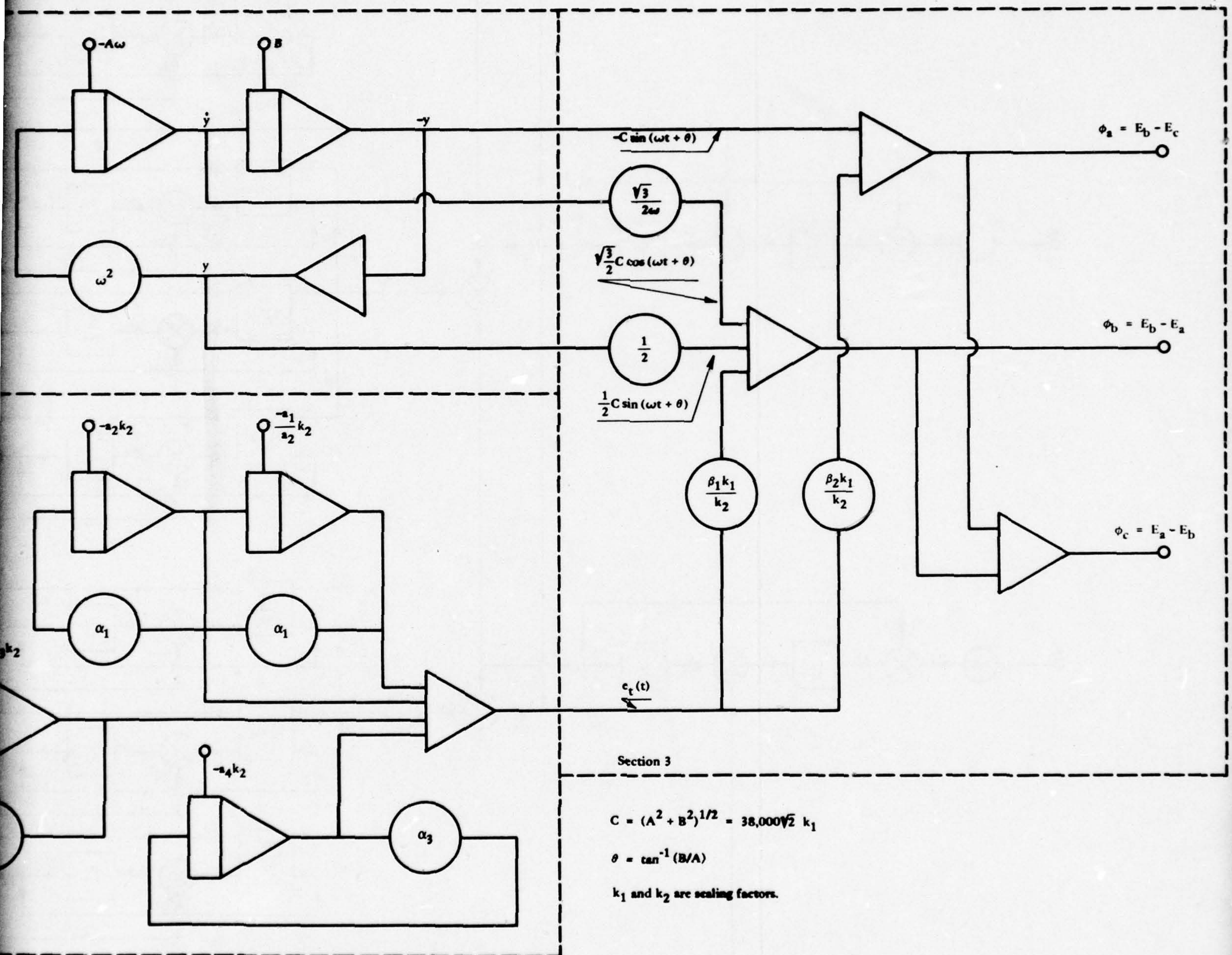


Figure 10. Schematic diagram of exciting sources simulation.

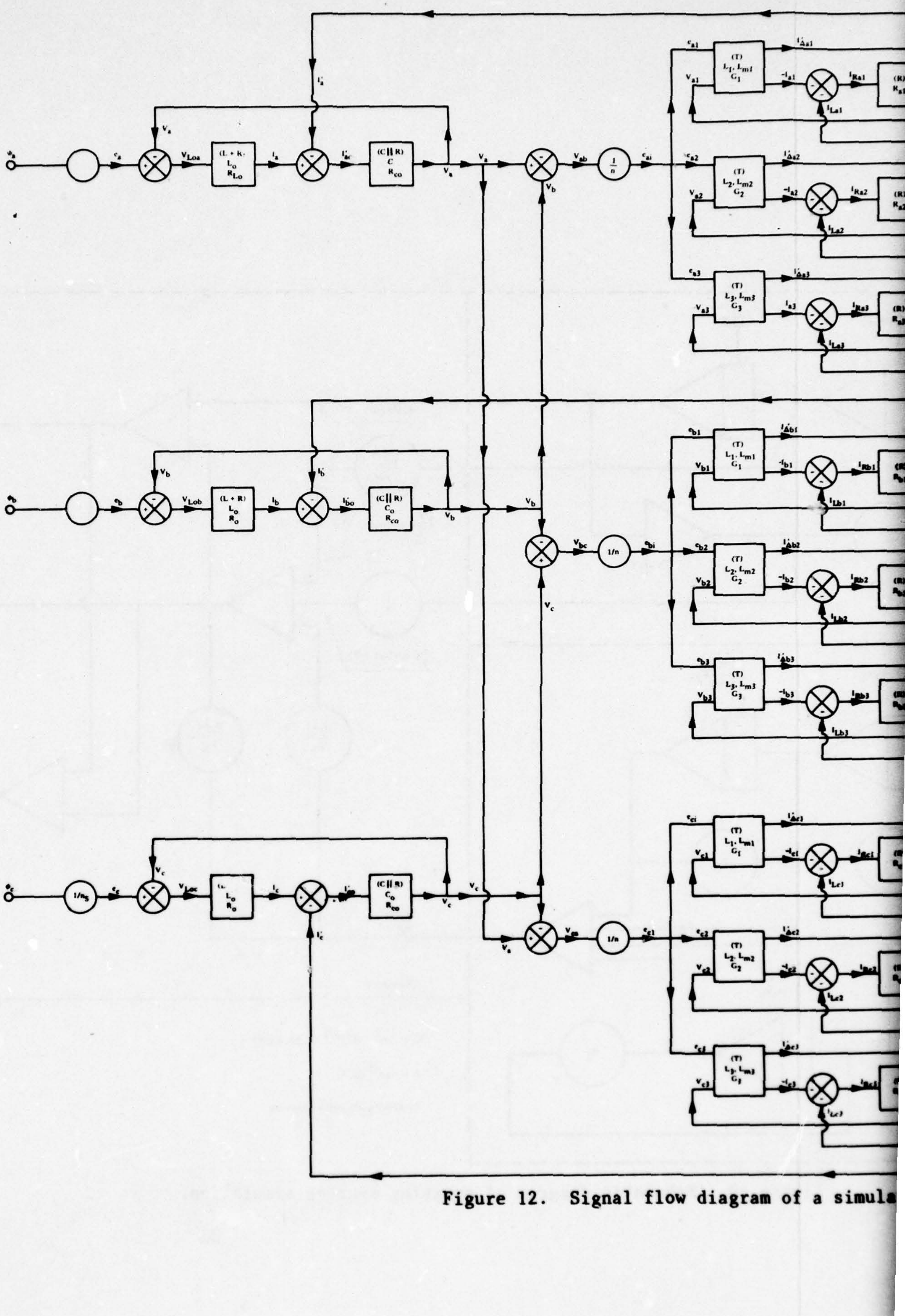
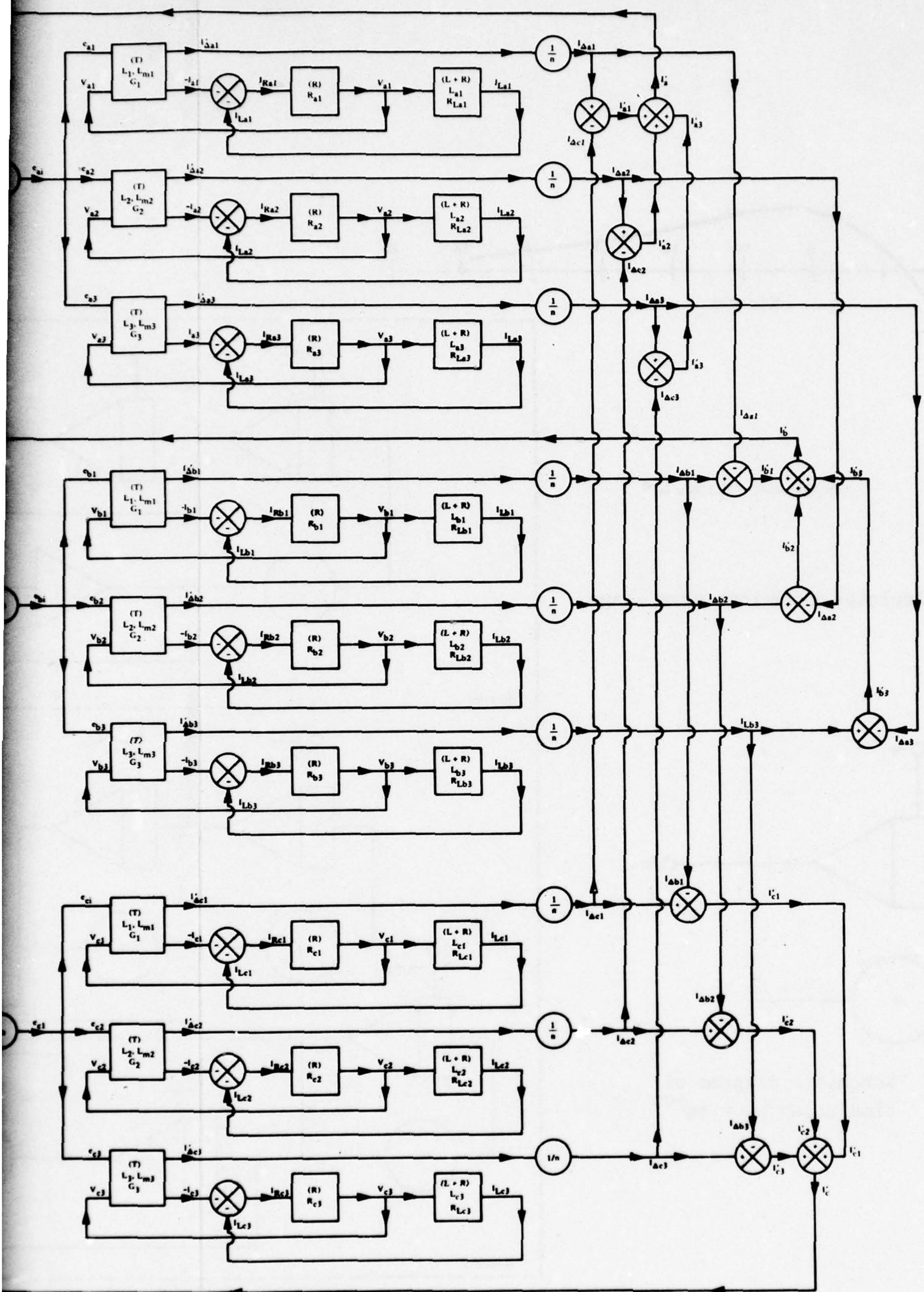
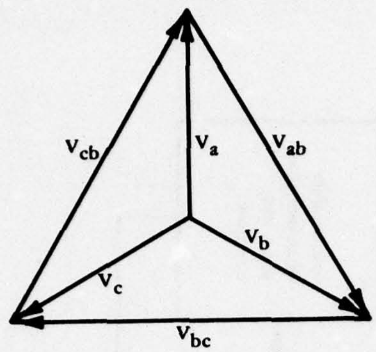


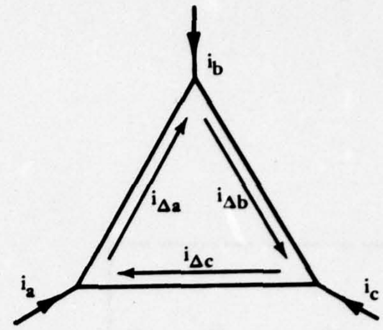
Figure 12. Signal flow diagram of a simula



l flow diagram of a simulating power system.

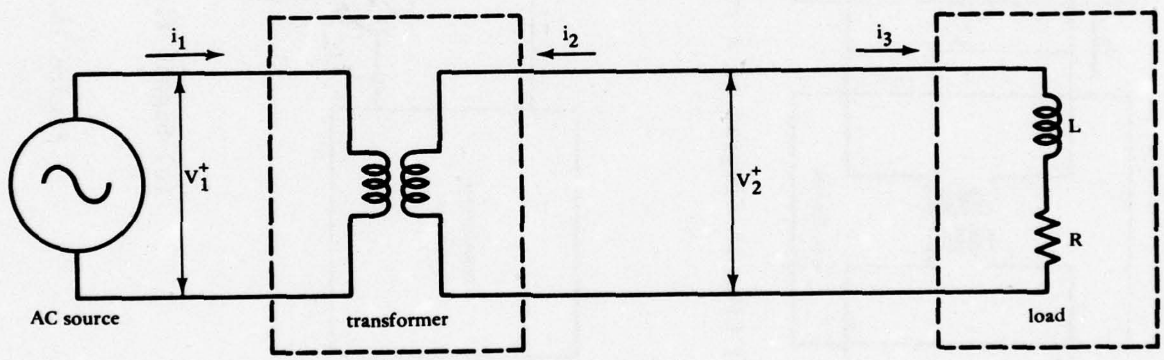


(a) Vector Relationship between line voltage and phase voltage.



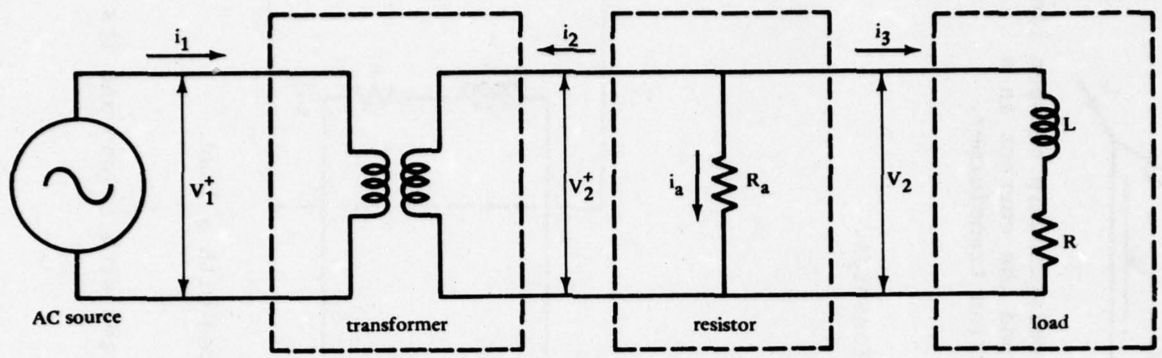
(b) Current relationship between line current and the current in a Δ-connection transformer.

Figure 13. Vector and current relationships.

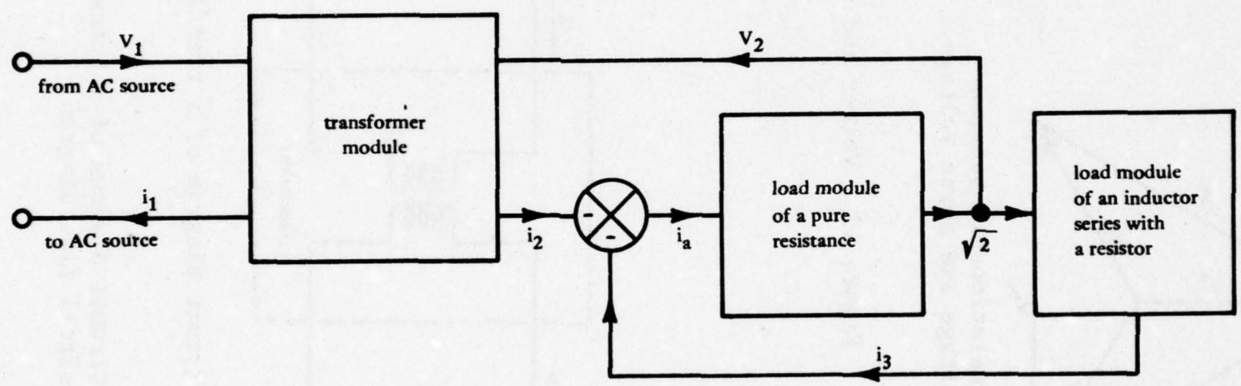


(a) Circuit diagram of a transformer connected with a load.

Figure 14. Circuit diagram of a transformer connected with a load and its signal flow diagram.



(b) Circuit diagram of a resistor inserted into (a).



(c) Signal flow diagram of (b).

Figure 14. Continued

Appendix A

CTF OF SIMULATING MODULES

Figure A-1 illustrates the basic circuit of the simulating module. The high gain operational amplifier in the circuit provides two conditions:

(1) $e_j << e_i$ and e_o

and

(2) $i_j << i_i$ and i_f

For simplification, these expressions can be considered as:

$$e_j = 0 \tag{A-1}$$

$$i_i = i_f \tag{A-2}$$

Thus, the circuit in Figure A-1 can be broken into two separate circuits as shown in Figure A-2a and b. The loop equations of the circuit in Figure A-2a can be written in matrix form as

$$\begin{bmatrix} e_i \\ o \end{bmatrix} = \begin{bmatrix} \Delta R_i & -x\,\Delta R_i \\ -x\,\Delta R_i & R_i + x\,\Delta R_i \end{bmatrix} \begin{bmatrix} i_a \\ i_i \end{bmatrix} \tag{A-3}$$

$$i_i = \frac{x\,\Delta R_i\,e_i}{\Delta R_i(R_i + x\,\Delta R_i) - x^2\,\Delta R_i^{\,2}}$$

$$\frac{i_i}{e_i} = \frac{1}{\frac{R_i}{x} + \Delta R_i(1-x)} = \frac{1}{K_i} \tag{A-4}$$

where

$$K_i = \frac{R_i}{x} + \Delta R_i (1-x) \tag{A-5}$$

and x is proportional to the wiper's position on the potentiometer ΔR_i; its value is between zero and one.

Since R_i and ΔR_i are fixed, value K_i is a function of x only.

The currents in the circuit of Figure A-2b can be written as

$$\left.\begin{aligned} i_f &= i_{f1} + i_{f2} \\ i_{f1} &= - C\, S\, e_o \\ i_{f2} &= i_{f4} - i_{f3} \end{aligned}\right\} \tag{A-6}$$

and

$$\left.\begin{aligned} (1-y)\, \Delta R_f\, i_{f3} + y\, \Delta R_f\, i_{f4} &= e_o \\ R_f\, i_{f2} + y\, \Delta R_f\, i_{f4} &= 0 \end{aligned}\right\} \tag{A-7}$$

Eliminating i_{f4}, i_{f3} from Equations A-6 and A-7 gives:

$$\begin{aligned} i_{f2} = i_{f4} - i_{f3} &= i_{f4} + \frac{y\, \Delta R_f\, i_{f4}}{(1-y)\, \Delta R_f} - \frac{e_o}{(1-y)\, \Delta R_f} \\ &= \frac{i_{f4}}{(1-y)} - \frac{e_o}{(1-y)\, \Delta R_f} \\ &= - \frac{R_f\, i_{f2}}{y(1-y)\, \Delta R_f} - \frac{e_o}{(1-y)\, \Delta R_y} \\ &= \frac{-y\, e_o}{R_f + y(1-y)\, \Delta R_f} \\ &= \frac{-e_o}{\frac{R_f}{y} + (1-y)\, \Delta R_f} = \frac{-e_o}{K_f} \end{aligned} \tag{A-8}$$

where

$$K_f = \frac{R_f}{f} + (1-y)\,\Delta R_f \tag{A-9}$$

and y is proportional to the wiper's position on the potentiometer ΔR_f; its value is between zero and one.

Since R_f and ΔR_f are fixed value K_f is a function of y only. Then

$$i_f = i_{f1} + i_{f2} = -\left(C\,S + \frac{1}{K_f}\right) e_o$$

$$\frac{e_o}{i_f} = -\frac{K_f}{K_f\,C\,S + 1} \tag{A-10}$$

Combining Equations A-2, A-4 and A-10, now gives the CTF of simulating modules:

$$\frac{e_o}{e_i} = \frac{i_i}{e_i}\left(\frac{e_o}{i_f}\right) = \frac{-(K_f/K_i)}{K_f\,C\,S + 1} = \frac{-A}{B\,S + 1} \tag{A-11}$$

where $A = K_f/K_i$

$B = K_f C$

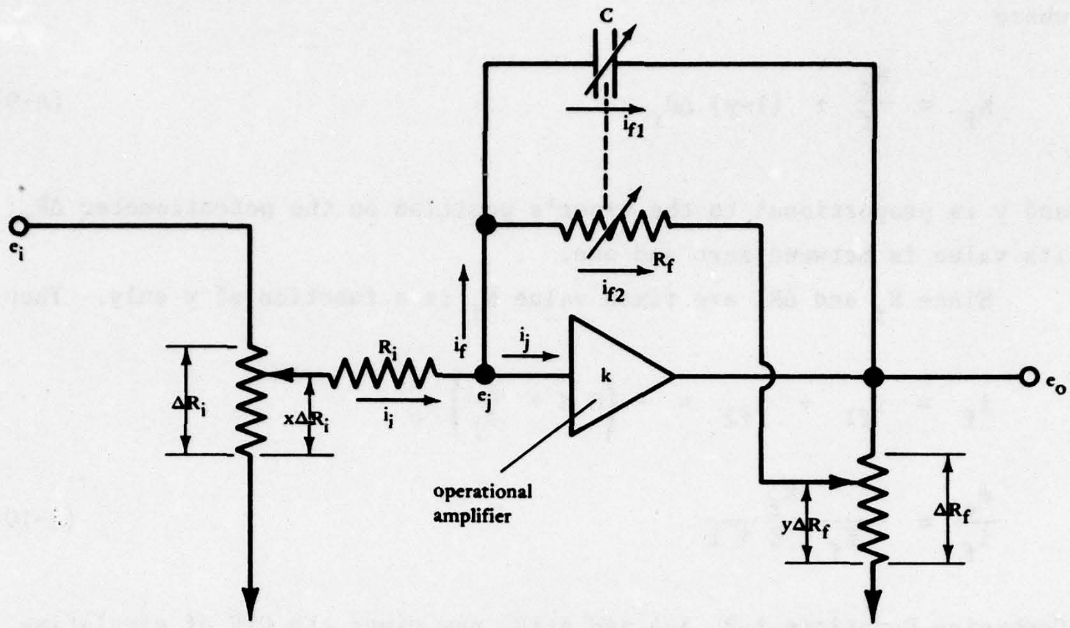


Figure A-1. Basic simulating model circuit.

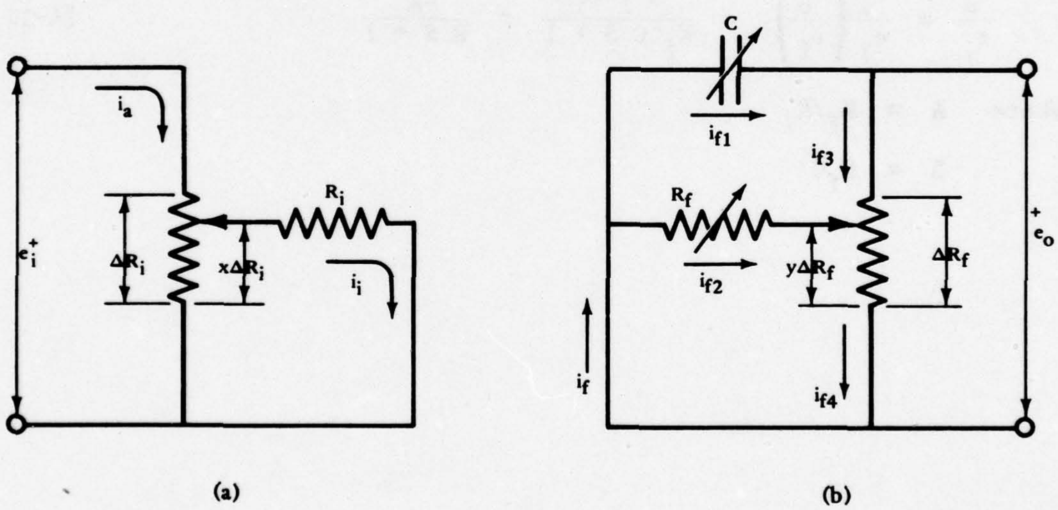


Figure A-2. Basic simulating model circuit separated into two circuits.

APPENDIX B

BASIC ENGINEERING APPLICATIONS OF PSS

This appendix is a reproduction of a manual issued by the Naval Civil Engineering Laboratory on the application of the equipment discussed in this report.

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A Manual on

BASIC ENGINEERING APPLICATIONS OF POWER SYSTEM SIMULATOR DC 750

MECHANICAL AND ELECTRICAL ENGINEERING DEPARTMENT

U.S. NAVAL CIVIL ENGINEERING LABORATORY

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FOREWORD

This manual is arranged for the purpose of providing a framework for a training course on the engineering applications of DC 750.

Consequently, the emphasis has been on the fundamentals rather than refinements.

Furthermore, since the readers are practicing engineers and scientists, introductory discussions have been left out, or reduced to bare minimum. Complementary discussions, selected based on the general interest of the participants, will be presented while conducting the course.

CONTENTS

I. INTRODUCTION

I.1 PHYSICAL MODEL

The first step in analyzing an engineering problem is forming a less complex and more idealized model of the actual physical system; the outcome of this step is the "physical model."

Example 1—In the mechanical system shown in Figure 1 each of the three components has mass, elastic deformation and internal friction (damping). A "physical model" of this system for the study of its dynamic behavior is formed by assigning to each element its predominant quality. Thus, the physical model shown in Figure 2 is obtained. In this idealized system the spring and the dash-pot have no mass, there is no elastic deformation in the dash-pot and the mass, and no damping anywhere except in the dash-pot.

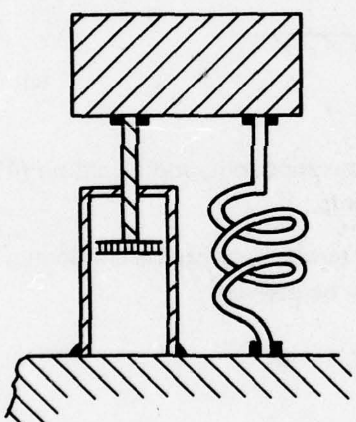


Figure 1

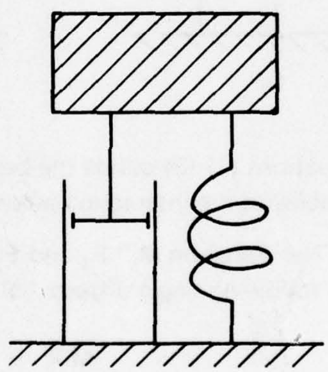


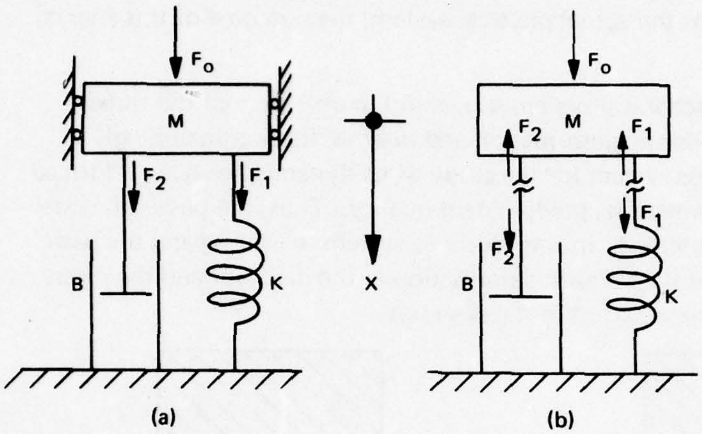
Figure 2

I.2 MATHEMATICAL MODEL

The second step in analyzing an engineering problem consists of expressing mathematically the cause-and-effect relationships of each component and the interactions amongst the components. The "mathematical model" is the outcome of this step.

Example 2—The physical model of Example 1 results in the following mathematical model (see Figure 3 for the definition of symbols):

$$\left\{\begin{aligned} \text{Net Force on M} &= M\ddot{X} && (1)\\ F_1 &= KX && (2)\\ F_2 &= B\dot{X} && (3)\\ \text{Net Force on M} &= F_o - (F_1 + F_2) && (4)\end{aligned}\right.$$



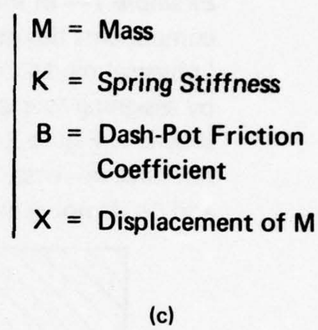


Figure 3

Equations (1)-(3) define the behavior of each component, and Equation (4) establishes the interaction amongst components.

If "Net Force on **M**," F_1 and F_2 are not of interest, they can be eliminated and the following single differential equation may be derived:

$$M\ddot{X} + B\dot{X} + KX = F_o \qquad (5)$$

I.3 COMPUTATION STAGE

The third step in analyzing an engineering problem is evaluating quantitatively the response, or behavior of the system, under a given set of conditions; this is the "computation stage."

Example 3—In the mathematical model of Example 2, the following quantities are given in a set of consistent units:

$$M = 1{,}000$$

$$B = 6{,}000$$

$$K = 144{,}000$$

At an instant when the mass **M** is at

$$X \triangleq X_o = 1$$

and has an upward velocity of 10, i.e.,

$$\dot{X} \triangleq V_o = -10$$

a downward force of 1,000, i.e.,

$$F_o = 1{,}000,$$

is applied. How does the mass **M** move from this instant on?

The purpose of "computation" in this example is to obtain the needed quantity, $X(t)$, from:

$$\left.\begin{aligned} \text{Net Force on } M &= M\ddot{X} \\ F_1 &= KX \\ F_2 &= B\dot{X} \\ \text{Net Force on } M &= F_o - (F_1 + F_2) \end{aligned}\right\} \text{Mathematical Model} \qquad (6)$$

subject to the ***input:***

$$F_o = 1{,}000 \qquad (7)$$

and the ***initial conditions:***

$$X_o = 1 \qquad (8)$$

$$\dot{X}_o = -10 \qquad (9)$$

II. METHODS AND MEANS OF COMPUTATION

II.1 INTRODUCTION

The computation stage of an engineering analysis can be carried out in a number of ways. The choice of the method is based on:

- Efficiency of computation,
- Accuracy requirement,
- Mode of presentation: numeric, graphic, etc.,
- Cost,
- Availability of computer and conflict with other users,
- Frequency of need to compute the same mathematical model for various input and initial conditions,
- Number of parameters and their range of variation,
- Optimization criteria (when applicable),
- Whether or not the calculation is to be carried out within a time limit while events are actually occurring (e.g., events associated with controlling a nuclear reactor, a satellite or a missile),
- Technical background and engineering proficiency of the analysis group, etc.

The methods and means of fulfilling the "computation" stage of an engineering analysis can be categorized as follows.

II.2 DIRECT SCALING OF PHYSICAL SYSTEMS (Prototype Method)

In this method the physical system is scaled dimensionally, e.g., wind tunnel evaluation of aircraft structures.

Example 4—The behavior of the dynamic system described by the mathematical model of Example 3 can be investigated by the prototype model shown in Figure 4 where:

$$m = 10^{-3} M = 10^{-3} \times 1{,}000 = 1$$

$$k = 10^{-3} K = 10^{-3} \times 144{,}000 = 144$$

$$b = 10^{-3} B = 10^{-3} \times 6{,}000 = 6$$

$$f_o = 10^{-3} F_o = 10^{-3} \times 1{,}000 = 1$$

$$x_o = X_o = 1$$

$$\dot{x}_o = \dot{X}_o = -10$$

time (prototype) = time (actual system)

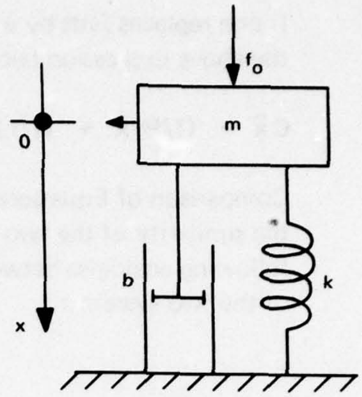


Figure 4

It can be easily shown that the mathematical models for the prototype and the original system are identical, the initial conditions are alike, and the displacements are equal at equal elapsed times.

II.3 DIRECT SIMULATION OF PHENOMENA (Direct Analog Method)

In this method the original phenomena is replaced by phenomena that can be used more conveniently, and implemented with less cost for the computation purposes, e.g., photoelastic stress determination of complex shapes.

A. Direct Analogy Using Passive Devices (Passive Analog Method)

In this approach, simple, elementary devices are used to simulate the effects of simple elements in the original system, e.g., an electrical capacitor for simulating a thermal capacitance, an electric resistor for a thermal resistance, etc.

Example 5—The physical model considered in Example 2 can be investigated by means of the electrical network of Figure 5. In fact, the mathematical model for this network is (refer to Figure 5 for definition of symbols):

$$I(t) = C \frac{dv}{dt} + \frac{1}{R} v + \frac{1}{L} \int_{-\infty}^{t} v \, dt$$

If one replaces $\int v dt$ by a new symbol, say **x**, the above expression becomes:

$$C\ddot{x} + (1/R)\dot{x} + (1/L)x = I(t) \qquad (10)$$

Comparison of Equations (5) and (10) shows the similarity of the two phenomena and the following analogies between the components of the two systems:

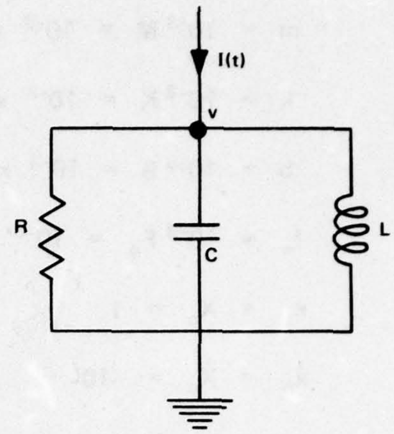


Figure 5

Mechanical System Equation (5)		Electric Model Equation (10)
M = Mass	⇔	C = Capacity
B = Viscous Friction	⇔	$\frac{1}{R}$ = Conductance
K = Spring Stiffness	⇔	$\left(\frac{1}{L}\right)$ = Inverse Inductance
F = Force	⇔	I = Current
$\dot{X}$ = Velocity	⇔	v = Potential

B. Direct Analogy Using Active Devices

In this method special electronic devices with amplifiers and other active circuits simulate simple, elementary components of the original system. The main limitation is that the electronic devices, while effective and trouble-free for integration, present many problems in differentiation; furthermore, these devices do not operate reversibly as their counterparts in the original system and often complex networks are needed for computer modeling of the reversibility.

Example 6—Arrange a direct analog for the system shown in Figure 6 with the assumption that analog devices shown in Figure 7 are available.

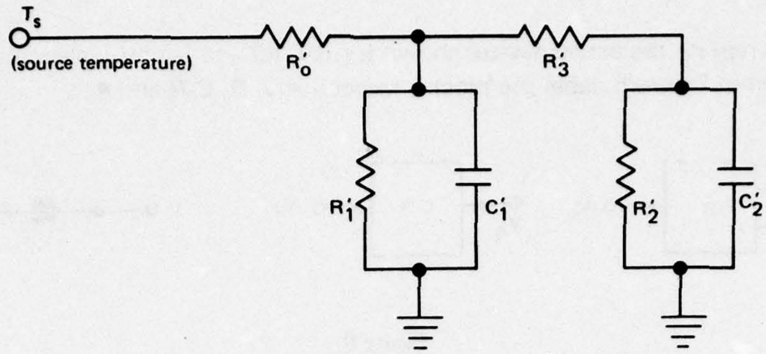


Figure 6

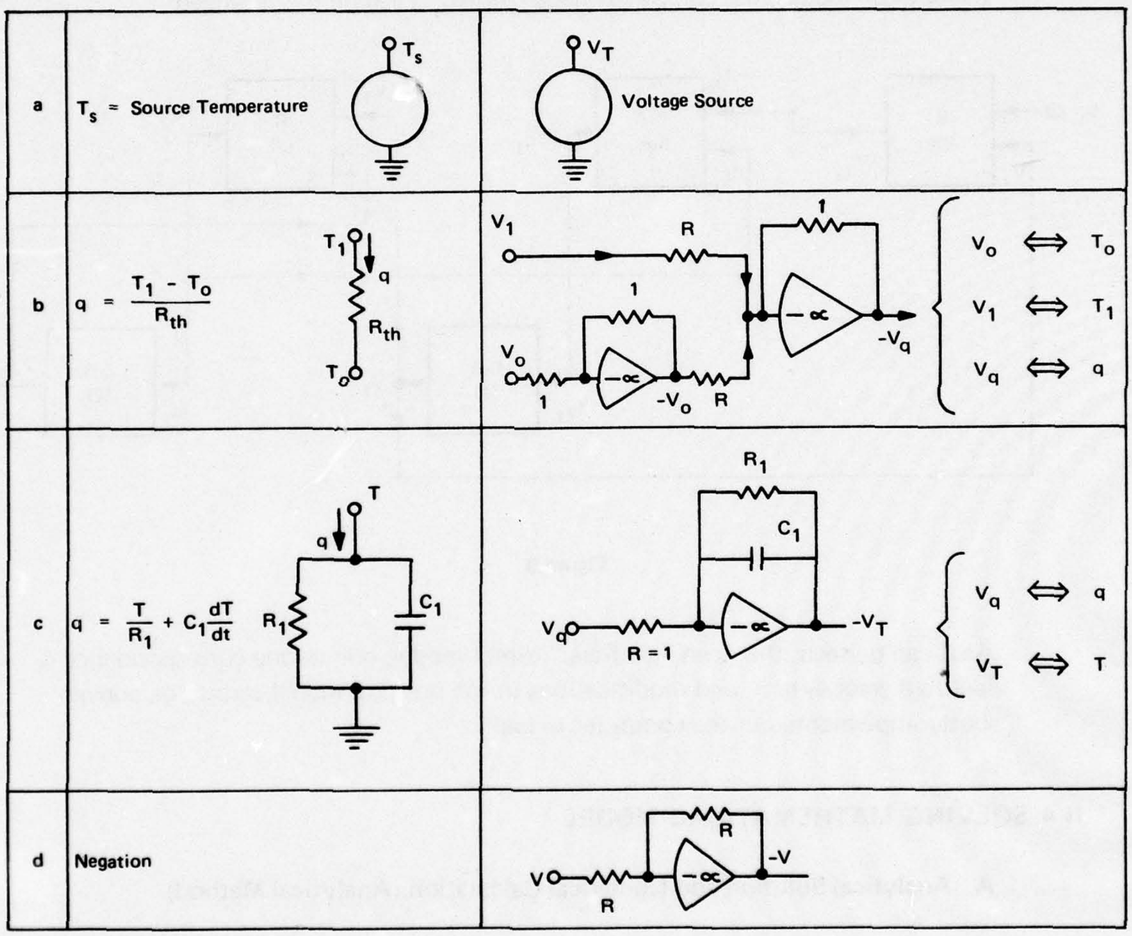


Figure 7

Let's replace the active devices shown for (b), (c) and (d) by the simple blocks shown in Figure 8; label the blocks, respectively, **R**, **C-R** and ■.

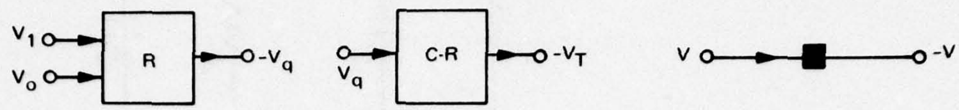


Figure 8

Using these blocks, the computer model shown in Figure 9 is arranged.

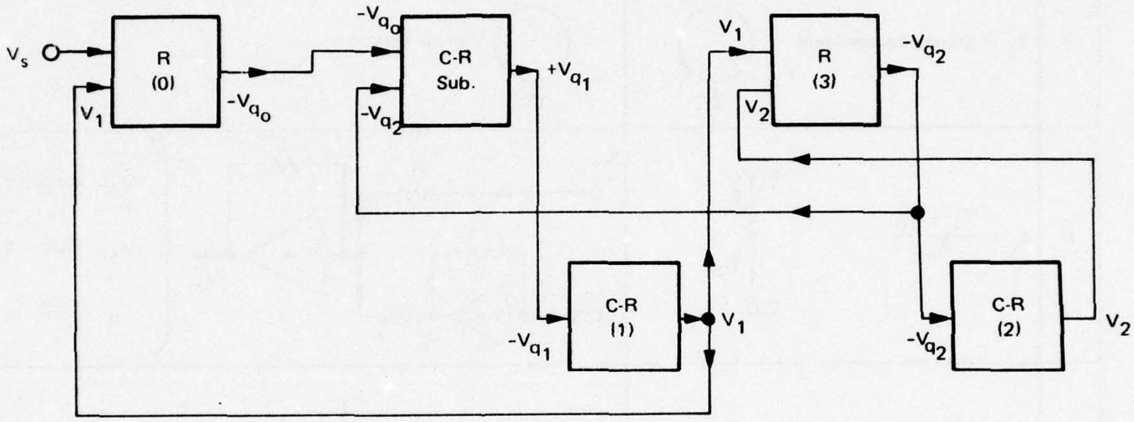


Figure 9

As it can be seen, this is an "artificial" direct model, one-to-one correspondance is lost to a great extent, and modifications in the physical model cannot be conveniently implemented in the computer model.

II.4 SOLVING MATHEMATICAL MODEL

A. Analytical Solution and Numerical Calculation (Analytical Method)

In this method, first, the mathematical model is solved analytically, and then evaluated quantitatively. Because of the usually complex form of analytical solutions the evaluation is almost always carried out numerically (or by means

of digital computers). In a digital computer, functions such as exponential, sine, cosine and their inverses, square root, cube root, Bessel functions, etc., are calculated by approximate series or iterative procedures in which only principal arithmetic operations are employed.

Example 7—The mathematical model of Example 2 and the numerical values of Example 3 result in the expression:

$$\ddot{X} + 6\dot{X} + 144X = 1 \quad \textbf{(Mathematical Model)} \tag{11}$$

The general solution of the above equation is:

$$X(t) = \frac{1}{144}\left[1 - \frac{4}{\sqrt{15}} e^{-3t} \sin(3\sqrt{15}\,t - \psi)\right]$$

$$+ X_o \frac{4}{\sqrt{15}} e^{-3t} \sin(3\sqrt{15}\,t - \psi)$$

$$+ \dot{X}_o \frac{1}{3\sqrt{15}} e^{-3t} \sin(3\sqrt{15}\,t)$$

where: $\psi \triangleq \tan(-\sqrt{15})$

By substituting X_o and $\dot{X}_o$ with initial values:

$$X_o = 1,$$

$$\dot{X}_o = -10,$$

for any given **t**, the value of **X(t)** is numerically calculated.

Note that in the above solution time is a continuous variable and **X(t)** can be evaluated at any chosen value of **t**.

B. Discrete Digital Computation (Digital Computer Method)

The mathematical models of engineering systems are generally integro-differential equations. With the exception of very simple mathematical models where analytical solutions are readily obtainable, the Discrete Digital Computation is used. In this method the derivatives and integrals in the mathematical model are replaced by finite difference and discrete integration formulae, the quantities of interest are solved for and, subsequently, computed digitally.

The accuracy of calculated results depends on the accuracy of finite difference and integration formulae. Instability problems resulting from calculations are quite frequent.

Example 8—The mathematical model of Example 7, Equation (11), is considered as an example. By using the finite difference formulae (see Figure 10 for the definition of symbols):

$$\ddot{X}_i = \frac{1}{h^2}(X_{i-1} - 2X_i + X_{i+1})$$

$$\dot{X}_i = \frac{1}{2h}(X_{i+1} - X_{i-1})$$

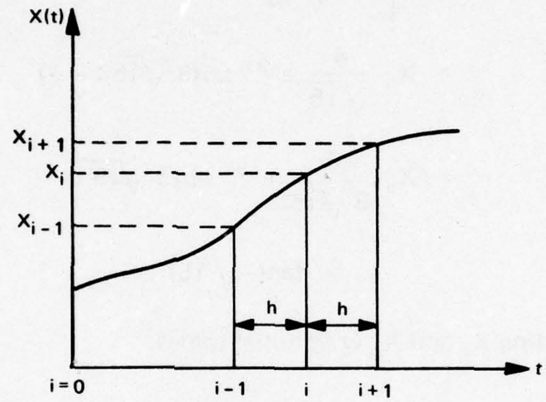


Figure 10

Equation (11) becomes:

$$\frac{1}{h^2}(X_{i-1} - 2X_i + X_{i+1}) + \frac{6}{2h}(X_{i+1} - X_{i-1}) + 144X_i = 1 \qquad (12)$$

from which:

$$X_{i+1} = \left[1 - \left(\frac{1}{h^2} - \frac{3}{h}\right)X_{i-1} + \left(\frac{2}{h^2} - 144\right)X_i\right] \Big/ \left(\frac{1}{h^2} + \frac{3}{h}\right) \qquad (13)$$

Therefore, using X_{i-1} and X_i, one can compute X_{i+1}. For obtaining X_1, however, a different approach is to be used. For example, since

$$\dot{X}_o = \frac{1}{2h}(X_1 - X_{-1}) = -10 \text{ (Given initial condition)}$$

one obtains:

$$X_{-1} = 20h + X_1 \tag{14}$$

and Equation (12), written for $i = 0$, results in:

$$\frac{1}{h^2}(X_{-1} - 2X_o + X_1) + \frac{3}{h}(X_1 - X_{-1}) + 144X_o = 1 \tag{15}$$

which, after replacing X_o with the initial condition 1 and X_{-1} with Equation (14), provides X_1, i.e.,

$$X_1 = -\frac{83}{2}h^2 - 10h + 1 \tag{16}$$

Now that X_o and X_1 are known, Equation (13) can be used to compute $X_2, X_3, \ldots$, successively.

This method of solution suffers particularly from discretization errors and limitations, as well as convergence problems.

C. Continuous Electronic Computation (Differential Analyzer)

In this method use is made of electronic devices which perform the principal arithmetic operations as well as integration with respect to time. Therefore, whenever there is only one independent variable (usually time) in the system, the outputs of the system can be computed as continuous functions.

This method, although based on the mathematical model, provides a computer model of the real physical system. The engineer can readily associate various signals to quantities in the original system and study end-to-end behavior of the system while the computation is in progress. Furthermore, rerunning the computation with new values of the parameters, or local modifications of the model can be accomplished readily and without extensive model changes.

Example 9—Solve the mathematical model of Example 7, Equation (11), i.e.,

$$\ddot{X} + 6\dot{X} + 144X = 1 \tag{17}$$

with the initial conditions:

$$X_o = 1, \qquad \dot{X}_o = -10$$

Since $\dot{X}$ and X are successive integrals of $\ddot{X}$, the graphical representation of Figure 11 always holds.

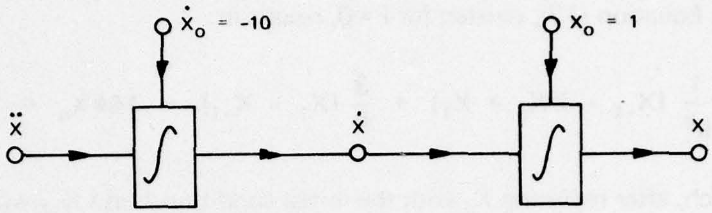


Figure 11

However, in order to satisfy the mathematical model, Equation (16), one must have at all times:

$$\ddot{X} = -6\dot{X} - 144X + 1 \tag{18}$$

Thus, $\ddot{X}$ in Figure 11, instead of being an assumed quantity, must be generated from $\dot{X}$ and X as shown in Figure 12.

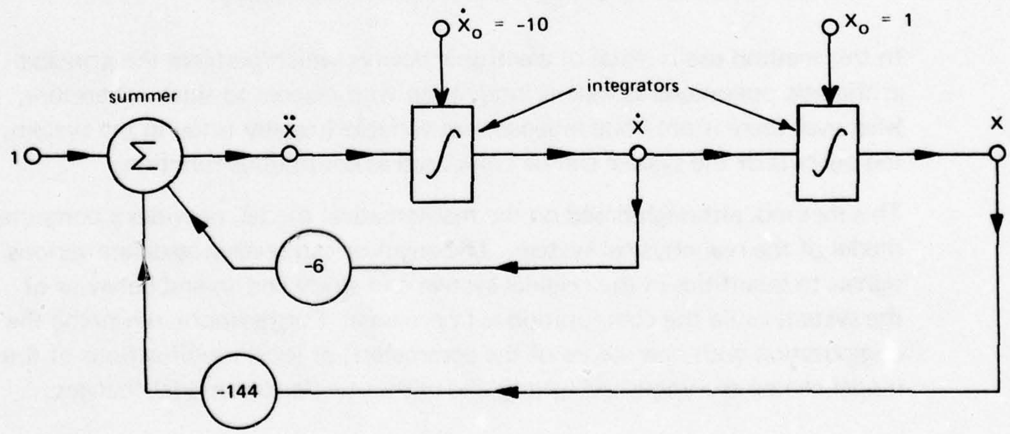


Figure 12

In a Differential Analyzer, electronic devices capable of integration and summation are available; however, these devices introduce a sign-change also. The Differential Analyzer model shown in Figure 13 is obtained from Figure 12 directly by introducing a sign change in each block and taking into consideration their effects throughout the network.

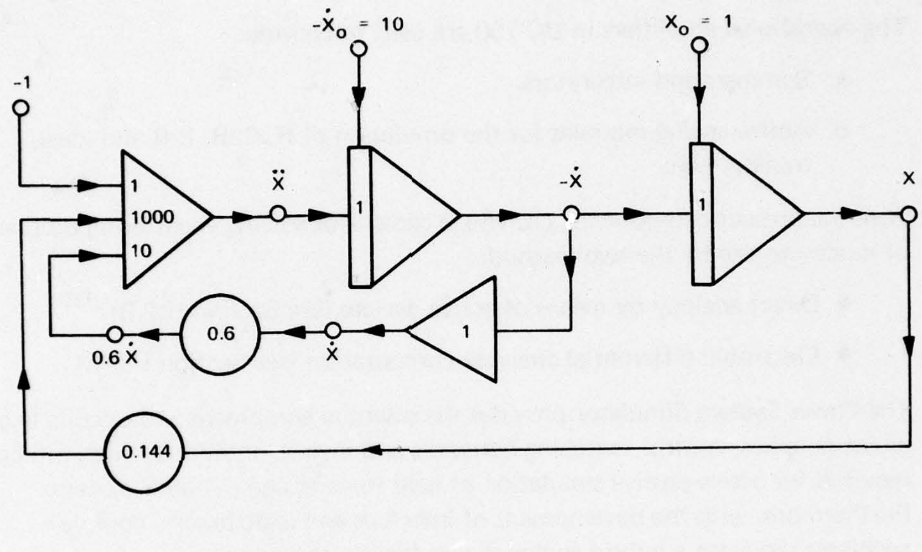


Figure 13

III. POWER SYSTEM SIMULATOR DC 750

III.1 CLASSIFICATION OF DC 750

The Power System Simulator (DC 750) is a special-purpose computer designed primarily for the simulation of power systems.

The fundamental component of DC 750 is an electronic unit called "operational amplifier." This device is basically a very high gain amplifier with an inherent sign change.

The operational amplifiers in DC 750 are used to provide:

a. Summers and integrators.

b. Active analog modules for the simulation of **R**, **CIIR**, **L-R** and ideal transformers.

With the present components, DC 750 is capable of solving engineering problems of moderate size by the two methods:

- Direct analogy by means of active devices (see Section II.2.B).
- Electronic differential analyzer computation (see Section II.3.C).

The Power System Simulator provides the essential equipment and circuits (e.g., power supplies, control switching networks and instrumentation) which will be required for active-passive simulation of heat transfer and dynamic systems. Furthermore, with the development of interface and logic blocks, complex problems requiring a hybrid analog-digital facility can be solved.

III.2 COMPONENTS OF DC 750

A. Power Supplies

Regulated reference DC power at the following voltages:

±10. , ±1. volts
±100. , ±10. , ±1. millivolts

are available. Each power supply is protected by special current limiting network and overload light indicator. All power supply outputs are with respect to a common system ground.

B. Potentiometers

There are two potentiometer panels, each panel contains 16 ten-turn, 10K-ohm potentiometers. The wiper of each potentiometer has a 10 volt, 14 ma current limiting lamp in series with its lead. The light serves as an overload indicator as well as a current limiter for protecting the potentiometer.

C. Transfer Trunks

There are 16 transfer trunks on each of the potentiometer panels numbered 00-16. The even numbered trunks have outlets on the control panel; all of the trunks are available on a distribution panel at the rear of the computer for external connections to other equipment.

D. Transistorized Voltmeter

A transistorized voltmeter is available on the control panel. A very high input impedance amplifier eliminates the loading effect. The voltmeter provides four ranges: 30 V., 10 V., 3 V. and 1 V.

E. Summers

The summers are formed by using the basic operational amplifiers in a feedback loop. There are altogether 10 summers available in 5 dual summer-integrator modules. Figure 14 shows input, output and related circuits of the summers.

F. Integrators

The integrators are formed by using the basic, chopper-stabilized, operational amplifiers in a feedback loop with provision of capacitor in the feedback branch. There are 10 integrators, one in each of the dual summer-integrator modules. Figure 15 shows input, output and related circuits of the integrators.

G. General Purpose Module

The general purpose module contains three units: a summer, an inverter and an integrator in one module. Furthermore, a number of feedback resistor and capacitor selections can be readily made by means of the range switch R_F/R_I.

Two potentiometers ΔR_I and ΔR_F serve to adjust the integrator input and feedback resistors for accurate gains.

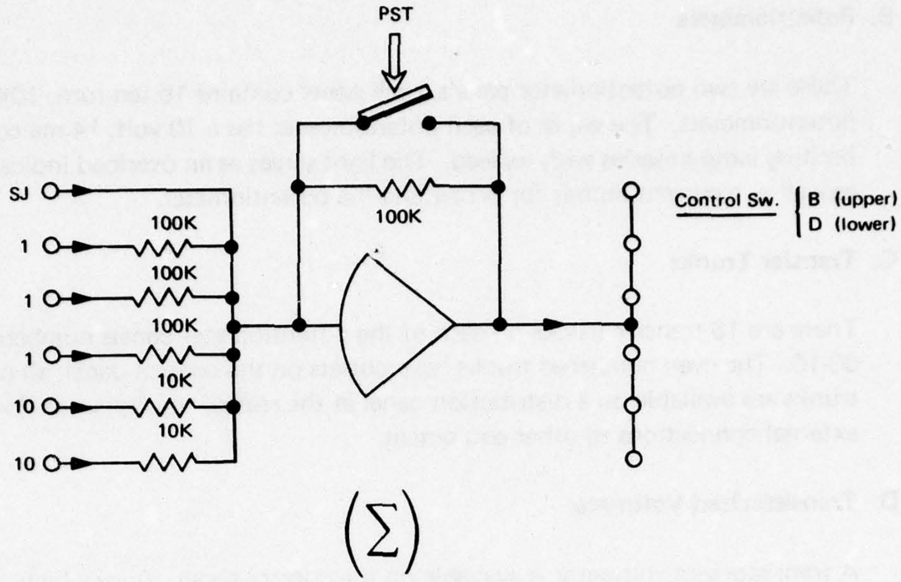


Figure 14. Summer

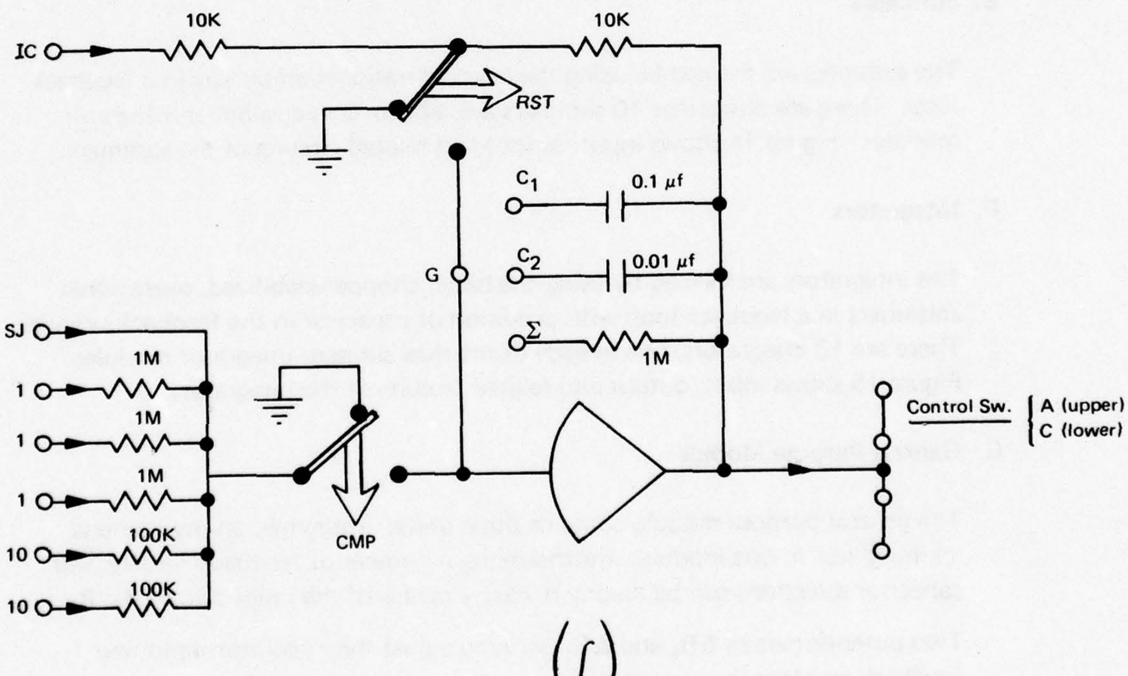


Figure 15. Integrator

The feedback capacitors are C_1 = 1. µf and C_2 = 0.1 µf. The range switch utilizes 1. µfd capacitor for the right-half of the dial (switch positions marked 10^6, 10^5, 10^4, 10^3, 10^2) and 0.1 µfd capacitor for the left-half positions (marked 10^5, 10^4, 10^3, 10^2, 10^1).

In the HG (High Gain) position, the operational amplifier of the integrator is essentially in open-loop position.

The inputs, outputs and related circuits are shown in Figure 16.

The three positions of the panel mode switch (toggle switch with positions: R. Only, Norm., Cal) and the range switch are described by the tables in Figure 16 in terms of the switches SW-1 and SW-2 shown in the figure.

H. Measurement Network and Controls

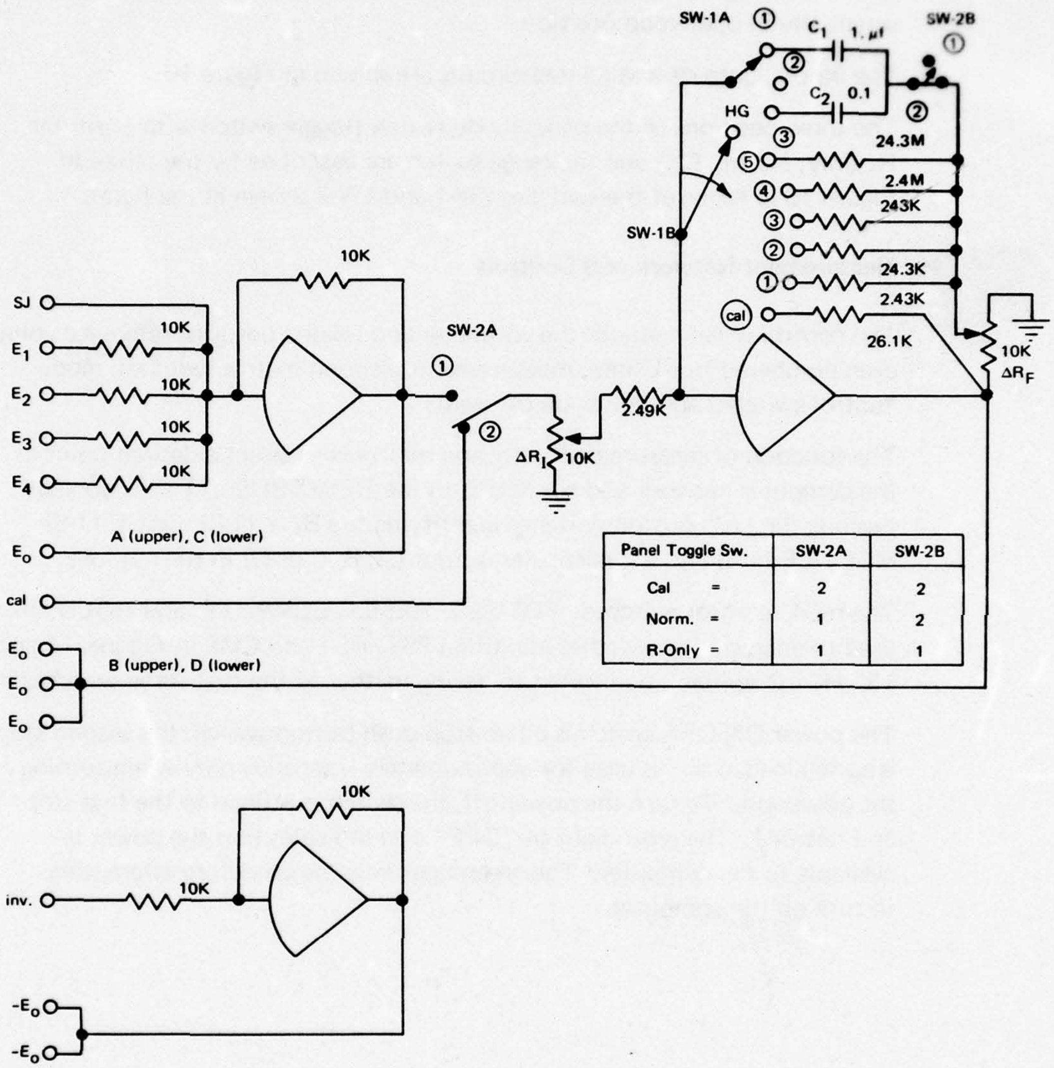
The control panel contains the voltmeter and related outputs, reference voltages, even-numbered trunk lines, measurement selection matrix switches, mode control switches and power on-off switch.

The function of measurement selection matrix is to select a desired point in the computer network and connect it to the READ BUSS. This is done by pushing the push-button switches identifying the BAY (1-3), CAGE (1-8), MODULE (1-8) and the particular output (A, B, C or D) in the module.

The mode-control switches: POT-SET, RESET, COMPUTE, and HOLD are used to energize the switches identified PST, RST and CMP in Figures 14 and 15. HOLD switch is equivalent to having neither of the first three switches on.

The power ON-OFF switch is a two-stop push-button switch; the second stop is spring-loaded and is used for approximately 5 seconds only when turning the power on. To turn the power off, the switch is pushed to the first stop and released. The green light of "OFF" sign indicates that the power is available to the computer. The green light must be on before attempting to turn on the computer.

	Left-Half C_1					Cal	Right-Half C_2					HG
R_F/R_I Range Sw.	10^1	10^2	10^3	10^4	10^5	Cal	10^6	10^5	10^4	10^3	10^2	HG
SW-1A	1	1	1	1	1	1	3	3	3	3	3	2
SW-1B	1	2	3	4	5	Cal	5	4	3	2	1	HG



Panel Toggle Sw.	SW-2A	SW-2B
Cal =	2	2
Norm. =	1	2
R-Only =	1	1

Figure 16. General Purpose Module

IV. SCALING

IV.1 INTRODUCTION

In solving an engineering problem on DC 750, all variables are represented by voltages within the range ±10 volts. When some or all of the variables in the original system have extremely large (or extremely small) magnitudes, scaling factors are required; this is the problem of "magnitude scaling."

Likewise, when the dynamic response of a system is to be investigated on DC 750, the limited frequency response of the computer, as well as the desirable time duration of the computer runs, necessitates introducing a time-scale; this is the problem of "time-scaling."

IV.2 MAGNITUDE SCALING (Normalizing Method)

Example 10

Consider the problem of forming a computer model for the mathematical model:

$$\ddot{x} + b\dot{x} + cx = f(t) \tag{19}$$

subject to the initial conditions

$$\dot{x}(0) = V_o, \quad x(0) = x_o \tag{20}$$

The computer model is shown in Figure 17

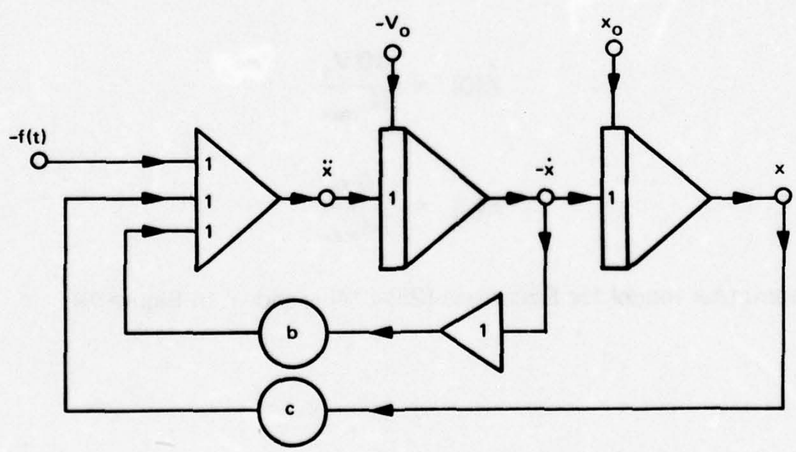


Figure 17

Let $|\ddot{x}|_{max}$, $|\dot{x}|_{max}$ and $|x|_{max}$ denote estimates of maximum magnitudes of $\ddot{x}$, $\dot{x}$ and x, respectively, and $|f(t)|_{max}$ be the maximum of the given function $f(t)$. Then, the new variables

$$X(t) = 10 \frac{x(t)}{|x|_{max}} \tag{21}$$

$$\dot{X}(t) = 10 \frac{\dot{x}(t)}{|\dot{x}|_{max}} \tag{22}$$

$$\ddot{X}(t) = 10 \frac{\ddot{x}(t)}{|\ddot{x}|_{max}} \tag{23}$$

$$F(t) = 10 \frac{f(t)}{|f(t)|_{max}} \tag{24}$$

are functions which remain within ±10 volts range.

To introduce the above variables, Equations (19) and (20) are rewritten as follows:

$$\frac{|\ddot{x}|_{max}}{10}\left(\frac{10\,\ddot{x}}{|\ddot{x}|_{max}}\right) + \frac{b|\dot{x}|_{max}}{10}\left(\frac{10\,\dot{x}}{|\dot{x}|_{max}}\right) + \frac{c|x|_{max}}{10}\left(\frac{10\,x}{|x|_{max}}\right) = \frac{|f(t)|_{max}}{10}\left(\frac{10\,f(t)}{|f(t)|_{max}}\right)$$

or

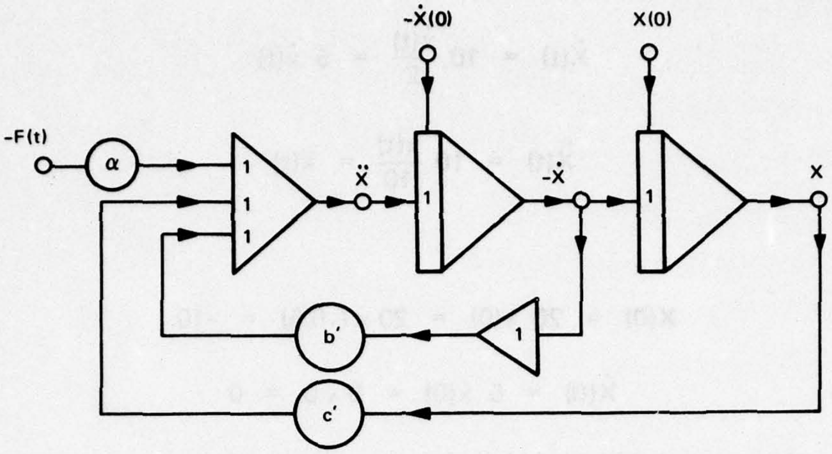
$$|\ddot{x}|_{max}\,\ddot{X} + b|\dot{x}|_{max}\,\dot{X} + c|x|_{max}\,X = |f(t)|_{max}\,F(t) \tag{25}$$

and

$$\dot{X}(0) = \frac{10\,V_o}{|\dot{x}|_{max}} \tag{26}$$

$$X(0) = \frac{10\,x_o}{|x|_{max}} \tag{27}$$

The computer model for Equations (25)-(27) is shown in Figure 18



$$\alpha = |f(t)|_{max}/|\ddot{x}|_{max}, \qquad b' = b|\dot{x}|_{max}/|\ddot{x}|_{max}$$

$$c' = c|x|_{max}/|\ddot{x}|_{max}, \qquad \dot{X}(0) = 10\,V_o/|\dot{x}|_{max}$$

$$X(0) = 10\,x_o/|x|_{max}$$

Figure 18

Example 11

As an illustration of normalizing method of scaling, consider:

$$\ddot{x} + 2\dot{x} + 16x = 0 \tag{28}$$

$$x_o = -0.5 \tag{29}$$

$$\dot{x}(0) = 0 \tag{30}$$

Let:

$$|x|_{max} = 0.5 \tag{31}$$

$$|\dot{x}|_{max} = 2. \tag{32}$$

$$|\ddot{x}|_{max} = 10. \tag{33}$$

Then:

$$X(t) = 10\,\frac{x(t)}{0.5} = 20\,x(t) \tag{34}$$

$$\dot{X}(t) = 10\,\frac{\dot{x}(t)}{2} = 5\,\dot{x}(t) \tag{35}$$

$$\ddot{X}(t) = 10\,\frac{\ddot{x}(t)}{10} = \ddot{x}(t) \tag{36}$$

and

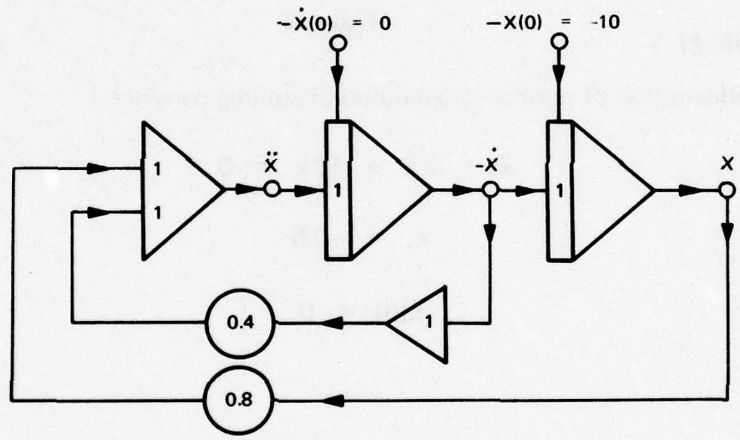
$$X(0) = 20\,x(0) = 20 \times (-0.5) = -10. \tag{37}$$

$$\dot{X}(0) = 5\,\dot{x}(0) = 5 \times 0 = 0 \tag{38}$$

Thus, the mathematical model becomes:

$$\ddot{X} + 0.4\dot{X} + 0.8X = 0 \tag{39}$$

The computer model is shown in Figure 19



$$\ddot{x} = \ddot{X}, \quad \dot{x} = \frac{1}{5}\dot{X} = 0.2\dot{X}, \quad x = \frac{1}{20}X$$

Figure 19

IV.3 TIME SCALING

Time is the only independent variable in the Differential Analyzer. Because of the frequency response limitations of the computer, or undesirably long or short time duration of the experiments in real time, scaling of time is often necessitated. Time-scaling is introduced at either mathematical modeling stage or computer modeling stage.

A. Time-Scaling Mathematical Model

Example 12

To present this method of time-scaling, consider the mathematical model

$$\frac{d^2x}{dt^2} + b\frac{dx}{dt} + cx = f(t) \tag{40}$$

with the initial conditions:

$$x(0) = x_o \tag{41}$$

$$\dot{x}(0) = V \tag{42}$$

If the computer time is denoted by τ, related to the real time **t** by

$$\tau = \alpha t, \tag{43}$$

then

$$\frac{dx}{dt} = \frac{dx}{d\tau}\frac{d\tau}{dt} = \alpha \frac{dx}{d\tau}, \tag{44}$$

$$\frac{d^2x}{dt^2} = \frac{d}{d\tau}\left(\frac{dx}{dt}\right)\frac{d\tau}{dt} = \alpha^2 \frac{d^2x}{d\tau^2}, \tag{45}$$

and the mathematical model, Equations (40)-(42), become:

$$\alpha^2 \frac{d^2x}{d\tau^2} + b\alpha \frac{dx}{d\tau} + cx = f\left(\frac{\tau}{\alpha}\right) \tag{46}$$

$$x(0) = x_o \tag{47}$$

$$\left.\frac{dx}{d\tau}\right|_{\tau=0} = \frac{1}{\alpha}\left.\frac{dx}{dt}\right|_{t=0} = \frac{1}{\alpha}x_o \tag{48}$$

B. Time-Scaling Computer Model

The only "time-conscious" component in DC 750 is the integrator. The time-constant of an integrator determines its rate of integration. To speed up the integration process, one must reduce the time constant. This is done by reducing the value of either the input resistor or the feedback capacitor.

If the time-constant of the integrator is reduced by reducing the input resistor **R** without changing **C**, since

$$\textbf{Integrator Gain} = \frac{C}{R}, \tag{49}$$

the gain is increased. This leads to an alternative way of implementing time-scaling of the computer model, namely, increasing the coefficient factor of input potentiometers by the required factor, or, distributing the time scale reduction factor between the gain of integrator and the input potentiometer coefficient.

Example 13

Consider the heating problem of a well-insulated body; the physical model is shown in Figure 20, and the thermal model is given in Figure 21.

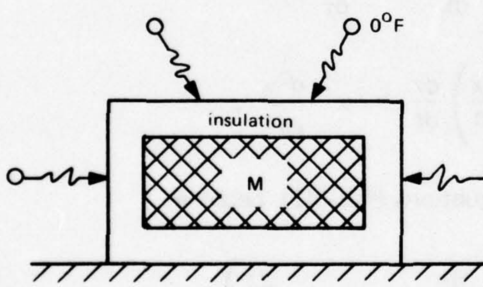


Figure 20

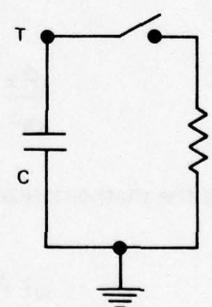


Figure 21

The mathematical model is:

$$C\frac{dT}{dt} = -\frac{T}{R}, \quad T(0) = T_o \tag{50}$$

where: **T** = temperature of **M**

C = thermal capacity of **M**

R = thermal resistance of insulation + thermal resistance of boundary

T_o = initial temperature of **M**

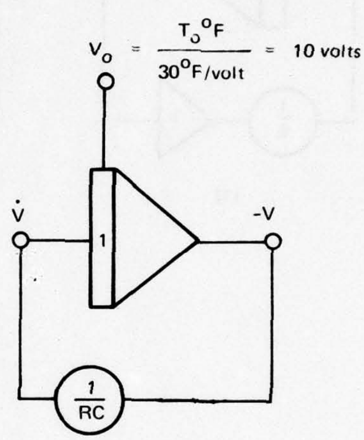
Assume the following numerical values:

$$C = 60\ \text{Btu}/^{o}\text{F}$$
$$R = 10^{o}\text{F.hr/Btu}$$
$$T_o = -300^{o}\text{F}$$

The computer model for this problem is shown in Figure 22.

The computer time exceeds 10 minutes. Therefore, time-scaling is desirable. To have computer runs completed in approximately 6 seconds, a time scale of 0.01 is required. Thus:

$$\tau = 0.01\,t, \qquad \alpha = 0.01 \qquad (51)$$



$T = 30 \times V$

$RC = 600$

Figure 22

Method 1—Time-Scaling Mathematical Model

Since:

$$\frac{dT}{dt} = \frac{dT}{d\tau}\frac{d\tau}{dt} = \alpha\frac{dT}{d\tau}, \qquad (52)$$

the mathematical model can be written as:

$$C\alpha\frac{dT}{d\tau} = -\frac{T}{R} \qquad (53)$$

and this is implemented in the computer model with replacing the potentiometer coefficient $1/\mathbf{RC}$ by $1/\alpha\mathbf{RC}$.

Method 2—Time-Scaling Computer Model

Time-Scaling of the computer model is accomplished by changing either the integrator time constant, or the integrator input potentiometer coefficient, or both.

Thus, to reduce the experiment time by a factor of 100, either of the computer models shown in Figure 23 may be used.

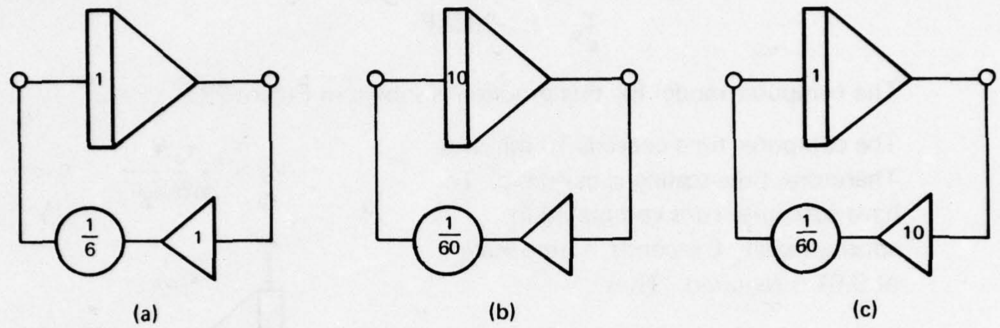


Figure 23

V. EXAMPLES OF ENGINEERING APPLICATIONS

V.1 THERMAL SYSTEMS

A. Steady-State Heat Flow

Example 14

Find the rate of heating an underground cryogenic storage tank (Figure 24).

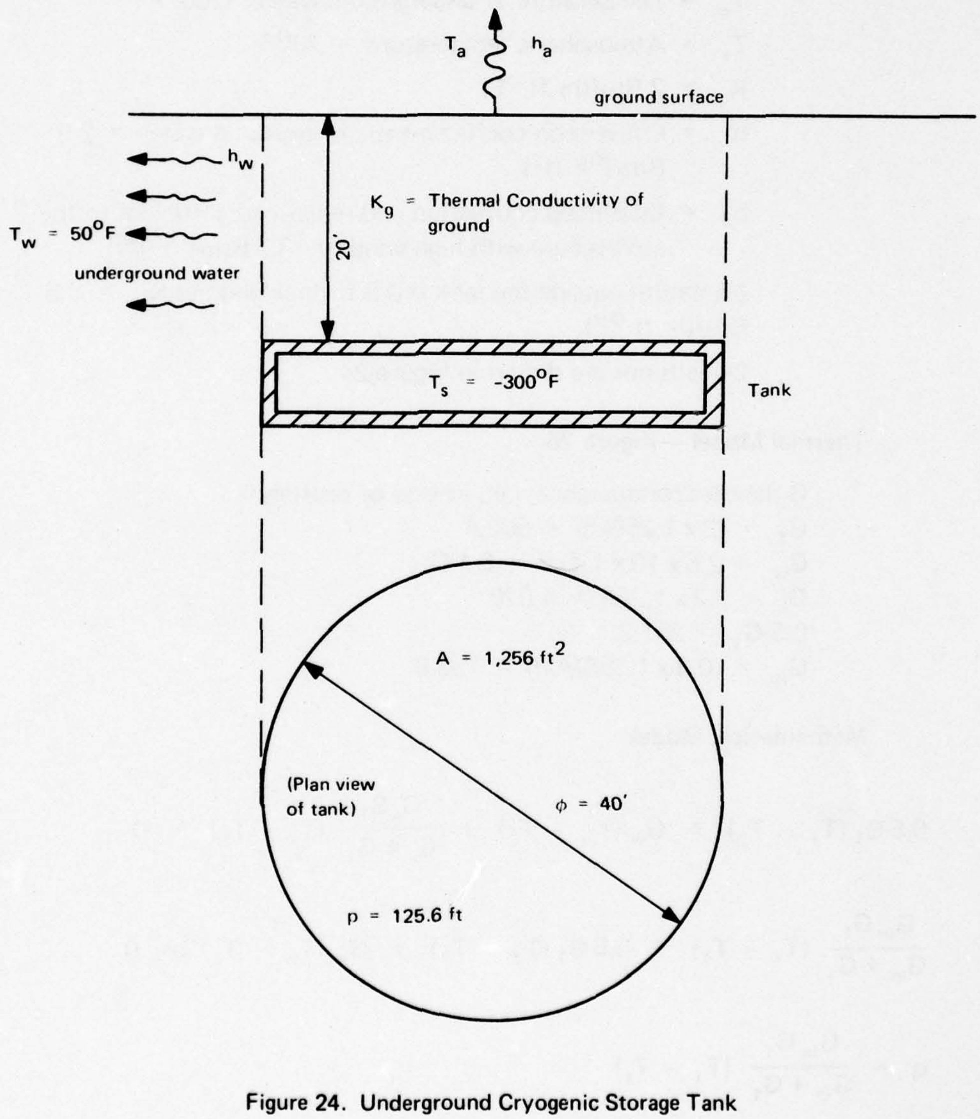


Figure 24. Underground Cryogenic Storage Tank

Assumptions:

1—One-dimensional flow (no corner effects).

2—Neglect ground freezing effect on properties.

3—Neglect heating of cryogenic due to cooling of the ground under the tank.

4—Use the following hypothetical values:

T_s = Temperature of tank (constant) = -300°F

T_w = Temperature of underground water = 50°F

T_a = Atmospheric temperature = 70°F

K_g = 2 Btu/(hr.ft.°F)

h_w = Convection coefficient to underground water = 2.5 Btu/(°F ft^2)

h_a = Combined convection and radiation coefficient to the atmosphere with high winds = 3.2 Btu/(°F ft^2)

Insulation outside the tank is 0.5 ft thick and has K_{in} = 0.3 Btu/(hr.ft.°F).

Dimensions are shown in Figure 24.

Thermal Model—Figure 25

G denotes conductance, i.e., inverse of resistance.

$G_1 = (2 \times 1{,}256)/5 = 502.4$

$G_w = 2.5 \times 10 \times 125.6 = 3{,}141$

$G_a = 3.2 \times 1{,}256 = 4{,}020$

$0.5\,G_1 = 251.2$

$G_{in} = (0.3 \times 1{,}256)/0.5 = 753.6$

Mathematical Model

$$0.5\,G_1 (T_1 - T_2) + G_w (T_w - T_2) + \frac{G_a G_1}{G_a + G_1} (T_a - T_2) = 0 \tag{54}$$

$$\frac{G_{in} G_1}{G_{in} + G_1} (T_s - T_1) + 0.5\,G_1 (T_2 - T_1) + G_w (T_w - T_1) = 0 \tag{55}$$

$$q = \frac{G_{in} G_1}{G_{in} + G_1} (T_1 - T_s) \tag{56}$$

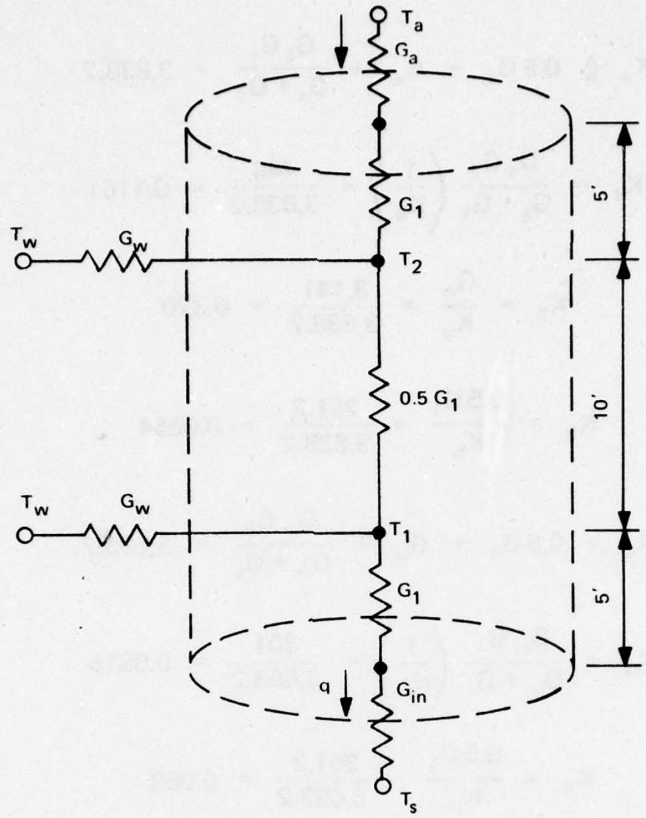


Figure 25. Thermal Model

Computer Model—Method 1 (Diff. An.-II.3-C)

Step One—Assume amplifiers have positive gains, Figure 26.

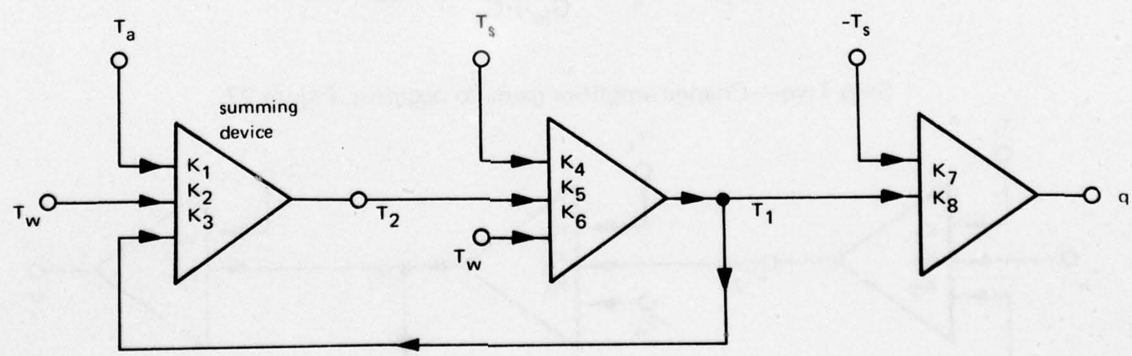


Figure 26. Computer Model; Positive Gains

$$K_o \triangleq 0.5\,G_1 + G_w + \frac{G_a\,G_1}{G_a + G_1} = 3{,}838.2$$

$$K_1 = \frac{G_a\,G_1}{G_a + G_1}\left(\frac{1}{K_o}\right) = \frac{446}{3{,}838.2} = 0.1161$$

$$K_2 = \frac{G_w}{K_o} = \frac{3{,}141}{3{,}838.2} = 0.820$$

$$K_3 = \frac{0.5\,G_1}{K_o} = \frac{251.2}{3{,}838.2} = 0.0654$$

$$K_o' = 0.5\,G_1 + G_w + \frac{G_{in}\,G_1}{G_{in} + G_1} = 3{,}693.2$$

$$K_4 = \frac{G_{in}\,G_1}{G_{in} + G_1}\left(\frac{1}{K_o'}\right) = \frac{301}{3{,}693.2} = 0.0815$$

$$K_5 = \frac{0.5\,G_1}{K_o} = \frac{251.2}{3{,}693.2} = 0.068$$

$$K_6 = \frac{G_w}{K_o} = \frac{3{,}141}{3{,}693.2} = 0.85$$

$$K_7 = K_8 = \frac{G_{in}\,G_1}{G_{in} + G_1} = 301$$

Step Two—Change amplifier gains to negative, Figure 27.

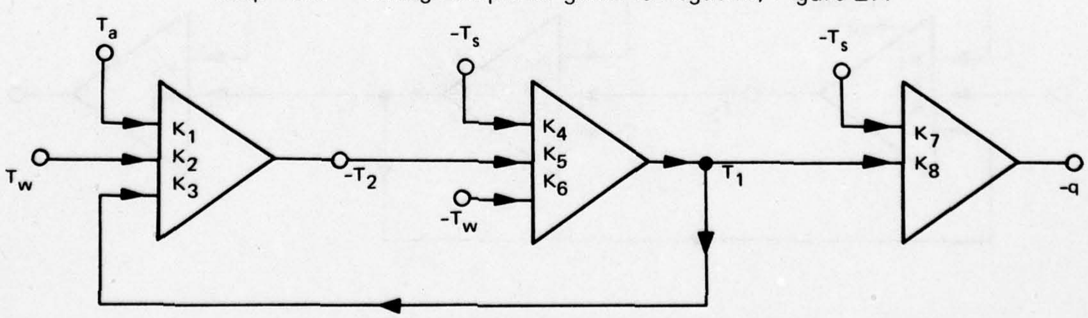


Figure 27. Computer Model Configuration

Let T_s = -300 be represented by -10 volts, i.e.,

$$V_{T_s} = T_s \times \frac{1}{30} = (-300) \times \frac{1}{30} = -10. \text{ volts}$$

Then:

$$V_{T_a} = T_a \times \frac{1}{30} = 70 \times \frac{1}{30} = 2.333 \text{ volts}$$

$$V_{T_w} = T_w \times \frac{1}{30} = 50 \times \frac{1}{30} = 1.667 \text{ volts}$$

$$V_q = \frac{1}{30} \left[(T_1 - T_s)\, G_i\, G_1 / (G_i + G_1) \right] = \frac{1}{30}\, q$$

Step Three—Introduce potentiometers for fractional gains, and summer gains for factors of 10. See Figure 28 for the result.

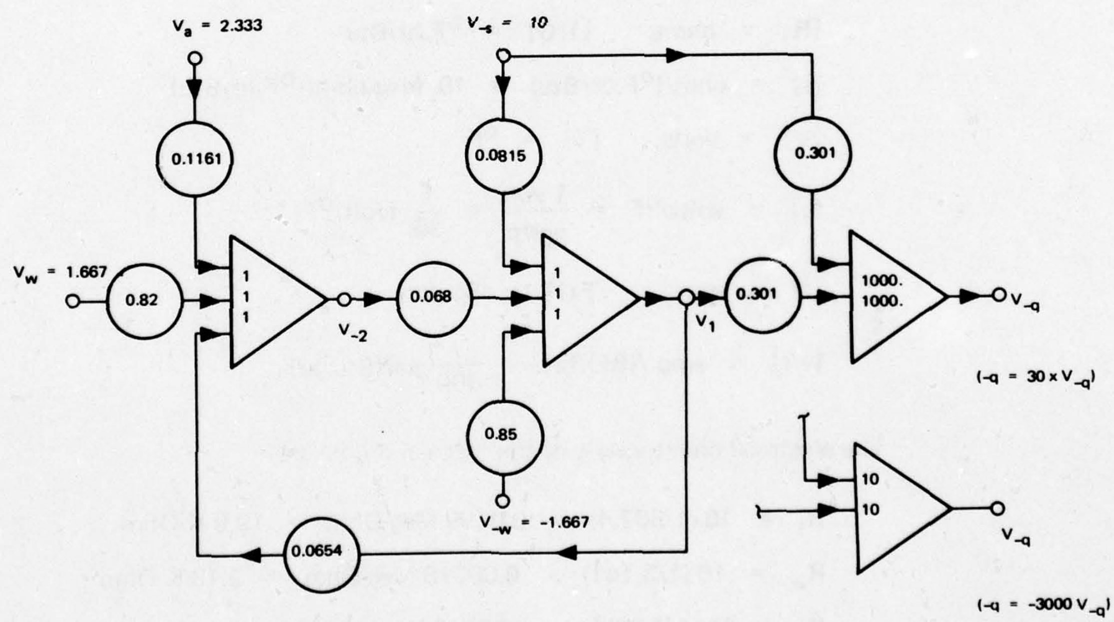


Figure 28. Final Computer Model (Method 1)

Discussion:

1—Change of dimensions and parameters without change of model configuration.

2—Getting additional information about the system behavior.

3—A more desirable scaling concept.

4—Reduction of network size.

Computer Model—Method 2 (Passive Analogy—II.2-A)

Step One—Conversion to Electrical Values.

Let:

$$R = r(1/G) \tag{57}$$

$$V = vT \tag{58}$$

then

$$I = (v/r)(T\,G) \tag{59}$$

The units are:

$[R]$ = ohms, $[1/G]$ = ^{o}F.hr/Btu

$[r]$ = ohm/(^{o}F.hr/Btu) = 10. Meg-ohm/(^{o}F.hr/Btu)

$[V]$ = volts, $[T]$ = ^{o}F

$[v]$ = volts/^{o}F = $\dfrac{1 \text{ volt}}{30^{o}\text{F}} = \dfrac{1}{30}$ (volt/^{o}F)

$[I]$ = amp., $[T\,G]$ = Btu/hr.

$[v/r]$ = amp./(Btu/hr) = $\dfrac{1}{300}$ μa/(Btu/hr)

The electrical counterparts of the thermal model are:

R_1 = 10 (1/502.4) = 0.0199 Meg-Ohm = 19.9 K-Ohm

R_w = 10 (1/3,141) = 0.00318 Meg-Ohm = 3.18 K-Ohm

R_a = 10 (1/4,020) = 0.00249 M = 2.49 K

R_{in} = 10 (1/753.6) = 0.001328 M = 1.33 K

$$V_s = -300\left(\frac{1}{30}\right) = -10 \text{ volts}$$

$$V_w = 50\left(\frac{1}{30}\right) = 1.667 \text{ volts}$$

$$V_a = 70\left(\frac{1}{30}\right) = 2.333 \text{ volts}$$

Step Two—Electrical Model, Figure 29.

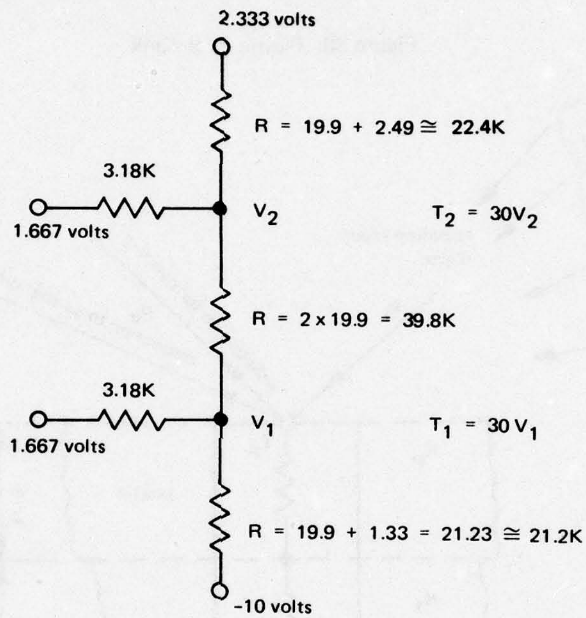


Figure 29. Computer Model (Method 2)

B. Transient Heat Flow

Example 15

Find the temperature-time heating curve of gasoline in a plastic fuel tank exposed to radiation from an uncontrolled fire, Figure 30.

The thermal system of Figure 30 may be replaced by the physical model shown in Figure 31.

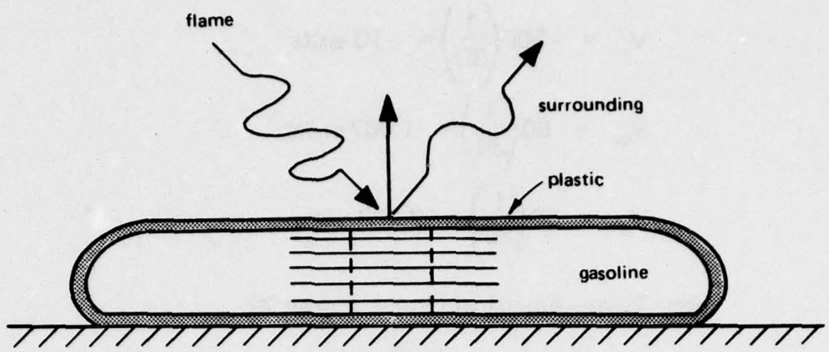


Figure 30. Plastic Fuel Tank

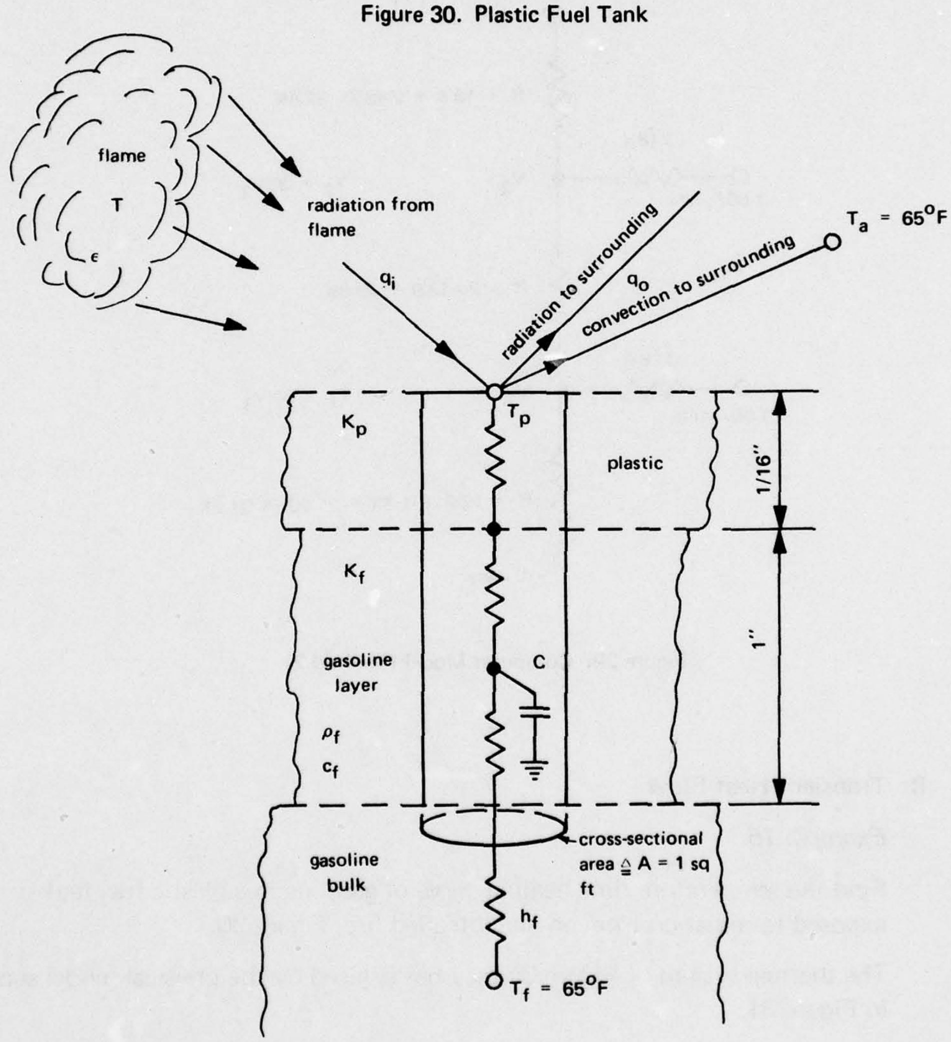


Figure 31. Physical Model

Dimensions and properties, all chosen hypothetically, are as follows:

q_i = 6,700 Btu/hr sq ft

$q_o = h_p (T_p - 65)$

$h_p \triangleq$ Effective radiation and convection heat transfer coefficient to surrounding, given in Figure 32 as a function of T_p

A = Cross-sectional area = 1 sq ft

K_p = 0.1 Btu/hr ft ^{O}F

K_f = 0.08 Btu/hr ft ^{O}F

c_f = 0.50 Btu/lb ^{O}F

ρ_f = 44 lbs/ft^3

h_f = 0.1 Btu/hr ^{O}F sq ft

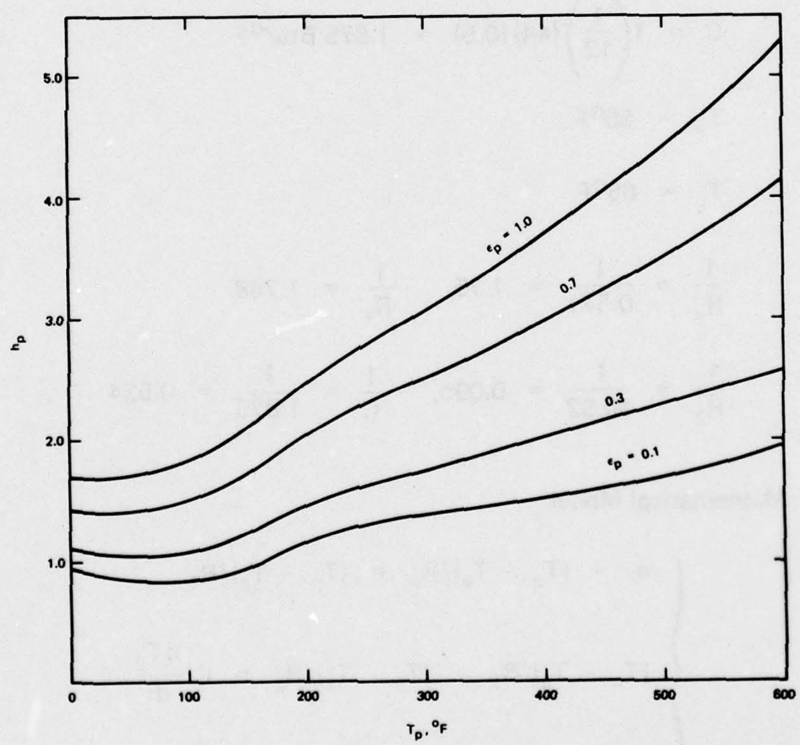


Figure 32. Effective Heat Transfer Coefficient to Surrounding Versus T_p for ϵ_p = 0.1, 0.3, 0.7 and 1.0.

Simplified Thermal Model, Figure 33

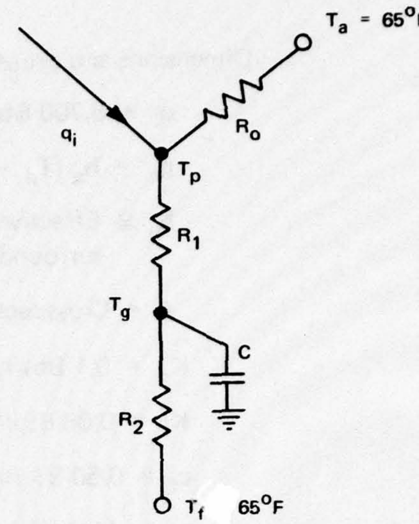


Figure 33. Thermal Model

$$R_o = \frac{1}{h_p A} = \frac{1}{h_p(1)} = \frac{1}{h_p}\left(\frac{hr.^oF}{Btu}\right)$$

For $\epsilon = 0.7$, $T_p = 150^oF$:

$$R_o = \frac{1}{1.75} = 0.571 \text{ hr}^o\text{F/Btu}$$

$$R_1 = \frac{(1/16)/12}{0.1(1)} + \frac{(1/2)/12}{0.08(1)}$$

$$R_1 = 0.572 \text{ hr.}^o\text{F/Btu}$$

$$R_2 = \frac{(1/2)/12}{0.08(1)} + \frac{1}{0.1(1)} = 10.52 \text{ hr}^o\text{F/Btu}$$

$$C = 1\left(\frac{1}{12}\right)(44)(0.5) = 1.875 \text{ Btu/}^o\text{F}$$

$$T_a = 65^oF$$

$$T_f = 65^oF$$

$$\frac{1}{R_o} = \frac{1}{0.571} = 1.75, \quad \frac{1}{R_1} = 1.748$$

$$\frac{1}{R_2} = \frac{1}{10.52} = 0.095, \quad \frac{1}{C} = \frac{1}{1.875} = 0.534$$

Mathematical Model

$$\begin{cases} q_i - (T_p - T_a)/R_o = (T_p - T_g)/R_1 & (60) \\ (T_p - T_g)/R_1 - (T_g - T_f)/R_2 = C\dfrac{dT_g}{dt} & (61) \\ T_g(t = 0) = T_f = 65^o & (62) \end{cases}$$

Measure all temperatures with respect to $T_a = T_f = T_g(0) = 65^{o}$, then, the mathematical model reduces to:

$$\begin{cases} q_i - T_p/R_o = (T_p - T_g)/R_1 \\ (T_p - T_g)/R_1 - T_g/R_2 = C\,\dfrac{dT_g}{d\theta} \end{cases}$$

$$T_g(t = 0) = 0 \quad \text{(Initial Condition)}$$

Computer Model—Method 1 (Diff. An., II.3-C)

Write the mathematical model as follows:

$$\begin{cases} T_p = \left(q_i + \dfrac{1}{R_1} T_g\right) \Big/ \left(\dfrac{1}{R_o} + \dfrac{1}{R_1}\right) & (63) \\ T_g = \dfrac{1}{C} \displaystyle\int_0^t \left[\dfrac{1}{R_1} T_p - \left(\dfrac{1}{R_1} + \dfrac{1}{R_2}\right) T_g\right] dt & (64) \\ T_g(0) = 0 & (65) \end{cases}$$

$$\frac{1}{\dfrac{1}{R_o} + \dfrac{1}{R_1}} = \frac{1}{3.498} = 0.286$$

$$\frac{1/R_1}{\dfrac{1}{R_o} + \dfrac{1}{R_1}} = \frac{1.748}{3.498} = 0.5$$

$$\frac{1}{C}\left(\frac{1}{R_1}\right) = 0.932\,, \qquad \frac{1}{C}\left(\frac{1}{R_1} + \frac{1}{R_2}\right) = 0.984$$

Step One—Assume positive gains for amplifiers. (Figure 34)

$$\begin{cases} T_p = 0.286\, q_i + 0.5\, T_g \\ T_g = \displaystyle\int_0^t [0.932\, T_p - 0.984\, T_g]\, dt \end{cases}$$

$$T_g(0) = 0$$

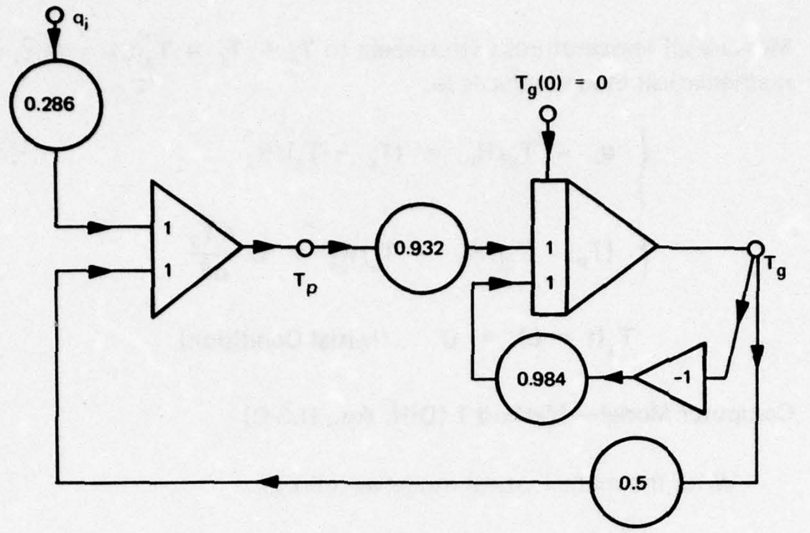


Figure 34. Computer Model; Positive Gains

Step Two—Change amplifier gains to negative, Figure 35.

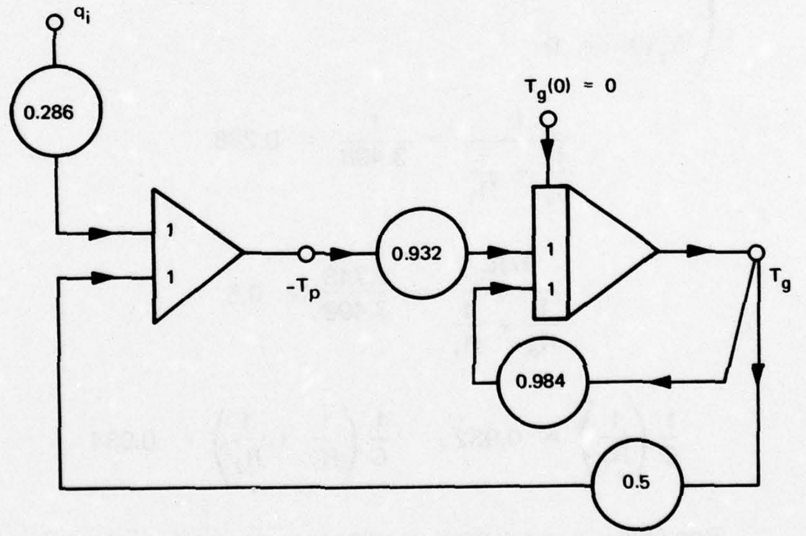


Figure 35

Step Three—Introduce Scale-Factors, Figure 36.

Let $T_{p,max}$ = 500, then:

$$500 = v(10) \therefore v = 50 \frac{\text{Degrees}}{\text{Volts}}$$

From: $$T_p = 0.286\, q_i + 0.5\, T_g$$

or $$\frac{T_p}{v} = 0.286 \frac{q_i}{v} + 0.5 \frac{T_g}{v}$$

one concludes that q_i must be scaled by v also, i.e.,

$$q_i\Big|_{\text{Comp. Model}} = \frac{1}{50} q_i\Big|_{\text{Thermal}} = \frac{6{,}700}{50} = 134$$

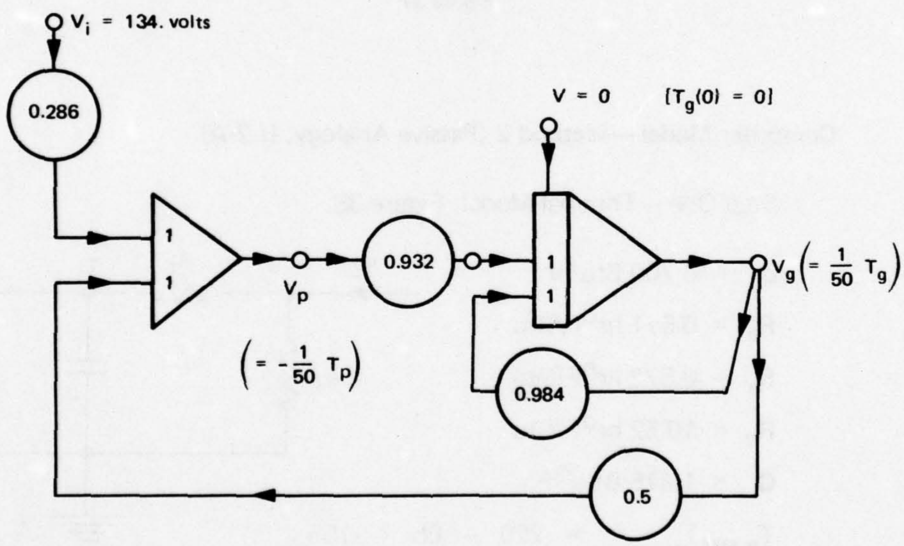
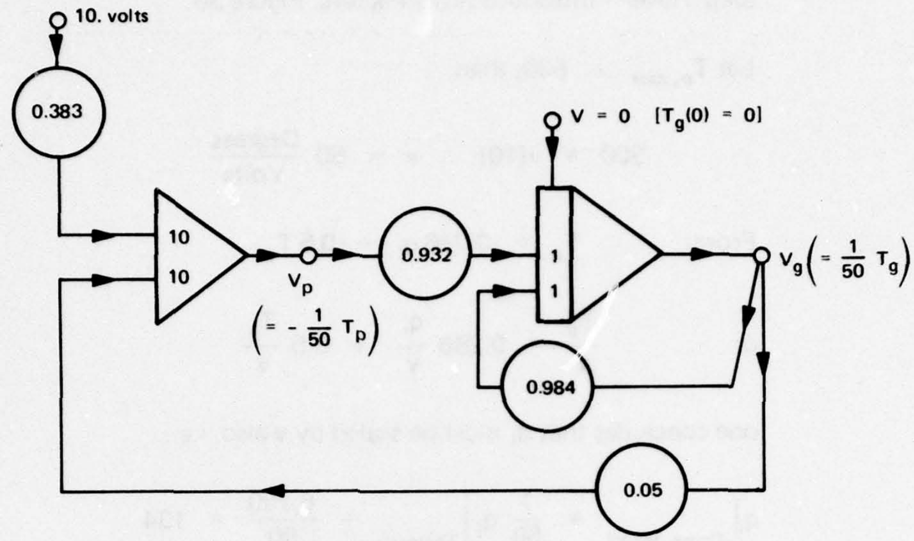


Figure 36

There is a problem: the highest available regulated voltage is 10. volts. A partially acceptable solution is given in Figure 37.



Note: 134 x 0.286 = 38.3 = 10 x 0.383 x 10.

Figure 37

Computer Model—Method 2 (Passive Analogy, II.2-A)

Step One—Thermal Model, Figure 38.

q_i = 6,700 Btu/hr

R_o = 0.571 hr^{O}F/Btu

R_1 = 0.572 hr^{O}F/Btu

R_2 = 10.52 hr^{O}F/Btu

C = 1.875 Btu/^{O}F

$T_{g, max}\Big|_{expected}$ = 220 - 65 = 155

"Ground" represents 65^{O}F

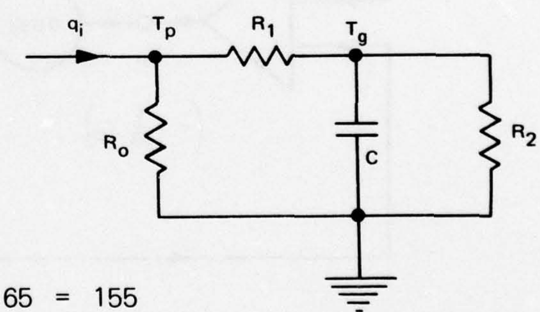


Figure 38

Step Two—Select scale factors and form Computer Model, Figure 39.

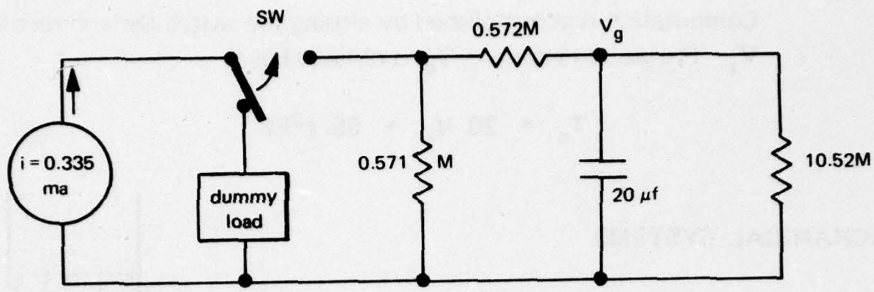


Figure 39

Let: $\quad 1 \text{ volt} \Leftrightarrow 20^oF$

$$20\,\mu fd \Leftrightarrow 1.875\ Btu/^oF$$

$$1.\ Meg \Leftrightarrow 1.^oF.hr/Btu$$

Then: $\quad \dfrac{1 \text{ volt}}{1 \text{ Meg}} = 1\,\mu a = 20\ Btu/hr$

$$20\,\mu fd \times 1\ Meg = 20\ sec = 1.875\ hr$$

or $\quad 1\ sec = 0.09375\ hr = 5.62\ min$

(How can you make the time scale 1 sec = 5 min?)

Computer Model Components:

$$i = q_i \left(\frac{1\,\mu a}{20\ Btu/hr}\right) = 6{,}700 \left(\frac{1}{20}\right) = 335\,\mu a = 0.335\ ma$$

$$R_o = 0.571 \times 1. = 0.571\ \text{Meg-ohms}$$

$$R_1 = 0.572\ \text{Meg-ohms}$$

$$R_2 = 10.52\ \text{Meg-ohms}$$

$$C = 20\,\mu fd$$

AD-A054 476 CIVIL ENGINEERING LAB (NAVY) PORT HUENEME CALIF F/G 9/3
POWER SYSTEM SIMULATOR.(U)
APR 78 K T HUANG
UNCLASSIFIED CEL-TN-1519 NL

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Computation is accomplished by closing the switch SW and recording V_g. The gas temperature, T_g, is obtained by:

$$T_g = 20\ V_g + 55.\ (^{o}F) \tag{66}$$

V.2 MECHANICAL SYSTEMS

A. Impact of Falling Bodies (Drop Test)

Example 16

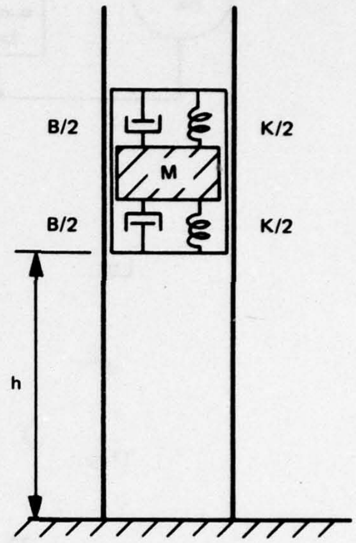


Figure 40

The package shown in Figure 40 is dropped to impact from a height **h**. Find the deceleration of **M** and its displacement with respect to the container after the impact. The following sets of parameters are to be considered:

$M = 1 \quad , \ 2\,gh = 400$

a: $B = 4.5 \quad , \ 18 \quad , \ 22.5 \quad$ with $K = 81$

b: $B = 6 \quad , \ 24 \quad , \ 30 \quad$ with $K = 144$

Assume statical deflection negligible compared with dynamical deflection.

Physical Model, Figure 41.

At the impact instant, the mass **M** is at $X = 0$ and has a velocity $V_o = \sqrt{2\,gh}$

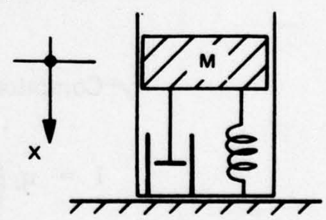


Figure 41

Mathematical Model

$$M\ddot{X} + B\dot{X} + KX = 0, \qquad \dot{X}(0) \triangleq V_o = \sqrt{400} = 20. \tag{67}$$

or

$$\ddot{X} = -(B/M)\dot{X} - (K/M)X \tag{68}$$

For case (a1) where: $B = 4.5$, $K = 81$, we have:

$$\ddot{X} = -4.5\dot{X} - 81X, \qquad B/M = 4.5, \qquad K/M = 81. \tag{69}$$

Values of **B/M** and **K/M** for various cases are:

	Case:	1	2	3
a	B/M:	4.5	18	22.5
	K/M:	81	81	81
b	B/M:	6	24	30
	K/M:	144	144	144

Computer Model, Figure 42.

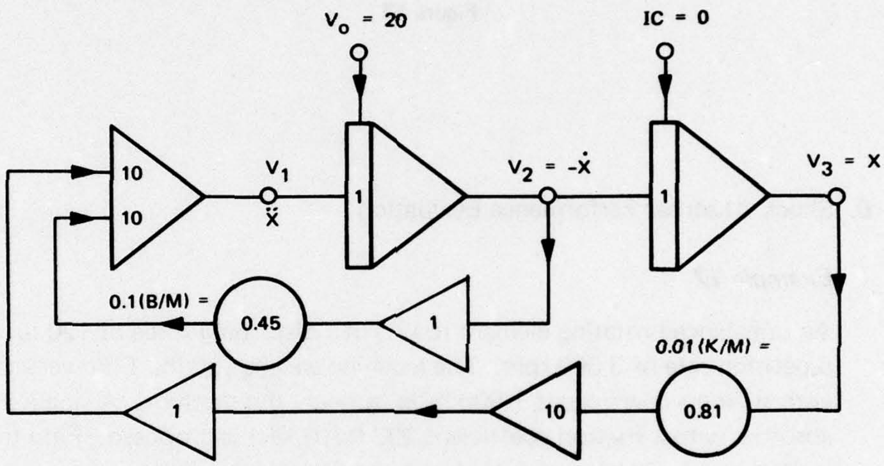


Figure 42

Note that $\dot{X}_o(0) = V_o = 20$ volts is beyond the operating voltage range of the computer.

The maximum deceleration is ~ 140 which is also beyond the operating voltage range of the computer.

To solve the above problems, modify the computer model as shown in Figure 43.

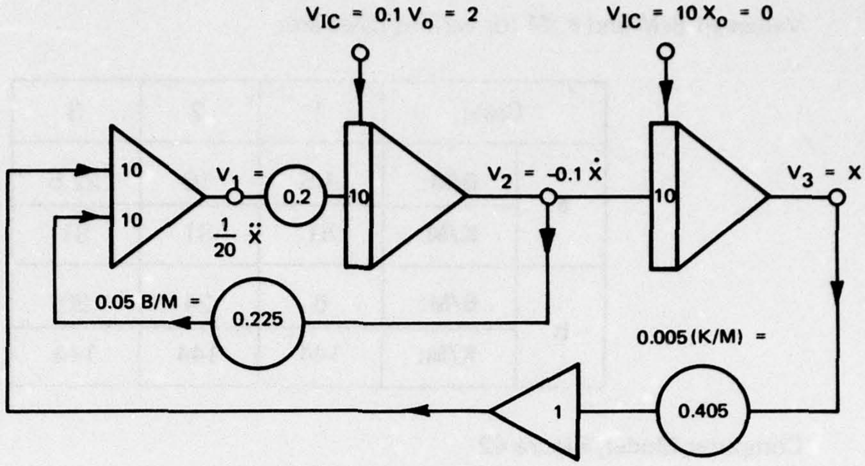


Figure 43

B. Shock Absorber Performance Evaluation

Example 17

An unbalanced rotating element results in a disturbing force of 120 lb. at a repetition rate of 3,000 rpm. The machine weighs 120 lb. Four vertical springs with stiffness coefficients 1,500 lb/in. support the machine. A single shock absorber with a friction coefficient 207 lb/(ft/sec) is proposed. Find the amplitude of vibration and maximum resulting acceleration.

Physical Model

The physical model is shown in Figure 44.

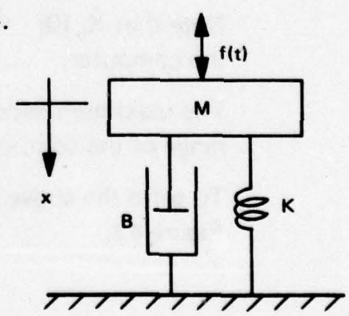


Figure 44

$$M = \frac{120}{32.2} = 3.72,$$

$$K = 1{,}500(4)(12) = 72{,}000$$

$$B = 207 \text{ lb/(ft/sec)}$$

$$f(t) = 120 \sin 314\, t$$

Mathematical Model

$$M\ddot{x} + B\dot{x} + Kx = f(t) \tag{70}$$

$$3.72\ddot{x} + 207\dot{x} + 72{,}000x = 120 \sin 314\,t \tag{71}$$

$$\ddot{x} + 56\dot{x} + 19{,}300x = 32.3 \sin 314\,t \tag{72}$$

Frequency of unbalance force is 3,000/60 = 50 Hz which is within the nominal frequency range of DC 750 computer.

Assume:

$$|x|_{max} = 5 \times 10^{-4}$$

$$|\dot{x}|_{max} = 0.2$$

$$|\ddot{x}|_{max} = 100$$

and normalize the mathematical model as follows:

$$|\ddot{x}|_{max}\ddot{X} + 56|\dot{x}|_{max}\dot{X} + 19{,}300|x|_{max}X = 3.23 \times 10 \sin 314\,t \tag{73}$$

where:

$$X = x/(5 \times 10^{-4}) = 2 \times 10^{3}x \tag{74}$$

$$\dot{X} = \dot{x}/0.2 = 5\dot{x} \tag{75}$$

$$\ddot{X} = \ddot{x}/100 = 0.01\ddot{x} \tag{76}$$

Rewrite the mathematical model as follows:

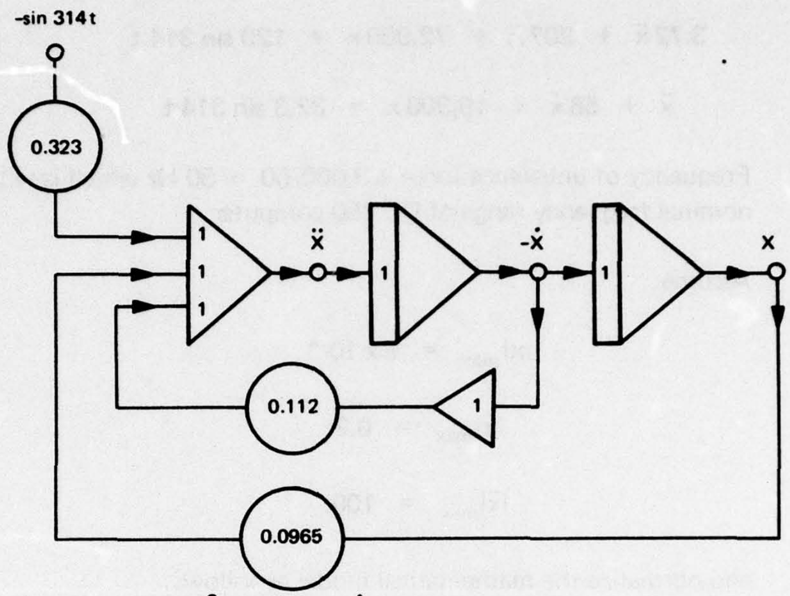
$$\ddot{X} = -\frac{56(0.2)}{100}\dot{X} - \frac{19{,}300(5)\,10^{-4}}{100}X + \frac{3.23}{100} \times 10 \sin 314\,t$$

or

$$\ddot{X} = -0.112\dot{X} - 0.0965X + 0.0323\,(10 \sin 314t) \tag{77}$$

Computer Model

The computer model is shown in Figure 45.



$x = 0.5\,X\,(10^{-3}), \quad \dot{x} = 0.2\,\dot{X}$

$\ddot{x} = 100\,\ddot{X}$

Figure 45

Discussion:

Computer modeling of a simplified version of VIBRA-LO.

V.3 FLUID SYSTEMS

A. Pipeline Distribution System

Example 18

In the pipeline distribution system shown in Figure 46, the flow-rate, q, versus inlet-outlet pressure difference, ΔP, is given for the three pipe sections in Figure 47. The pressure at the pump outlet, P_1, and at the receiving reservoirs, P_2 and P_3 are known:

$$P_1 = 80 \text{ psi}, \quad P_2 = 10 \text{ psi}, \quad P_3 = 20 \text{ psi}$$

Find the flow-rates q_2 and q_3.

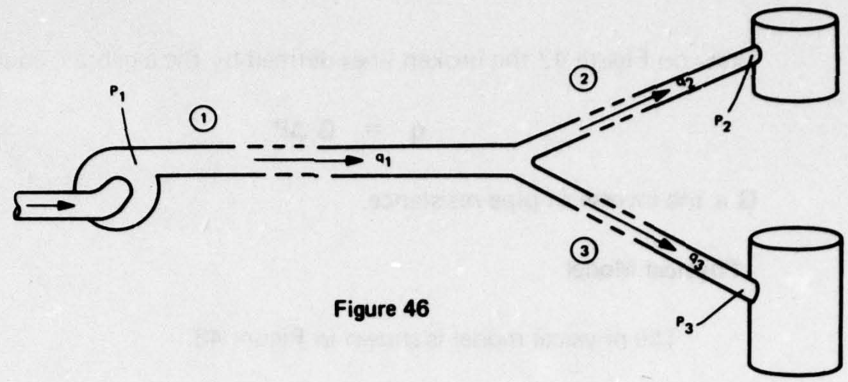


Figure 46

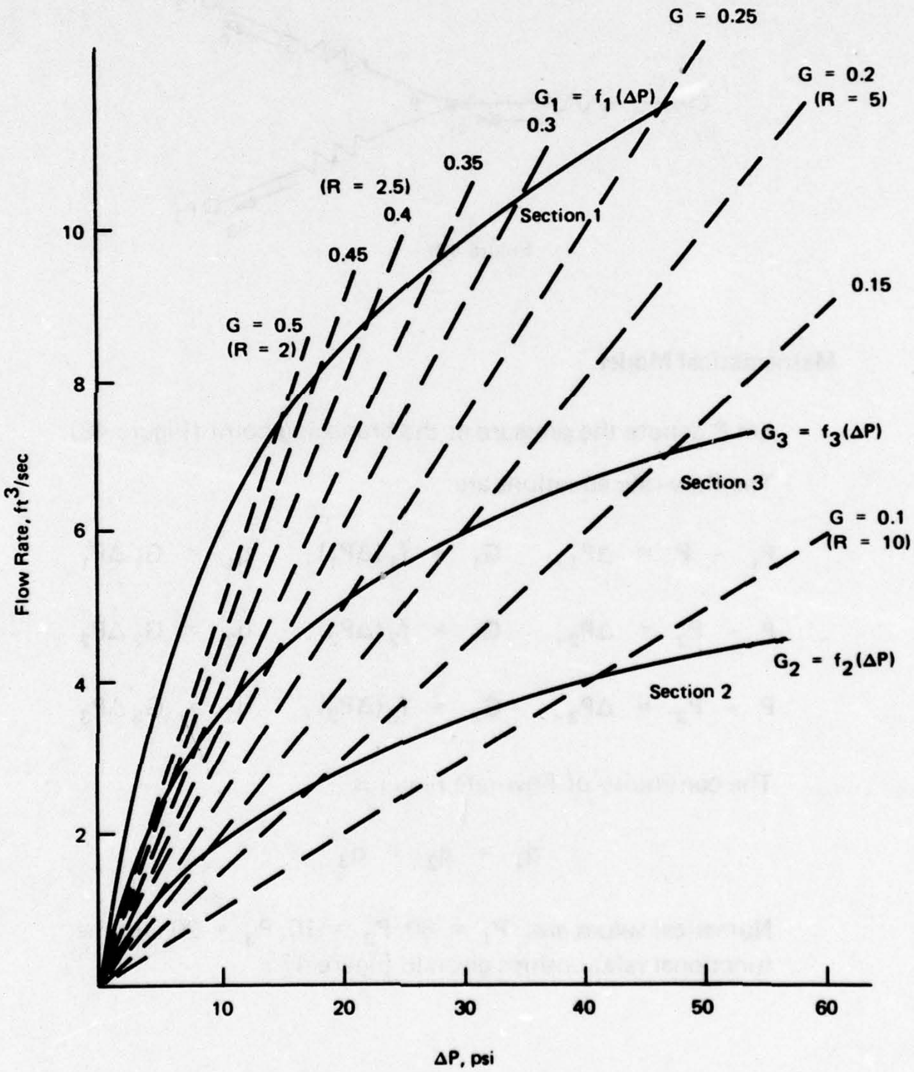


Figure 47. Pipe Sections Resistance Characteristics

Draw on Figure 47 the broken lines defined by the algebraic equations

$$q = G\,\Delta P \tag{78}$$

G is the inverse of pipe resistance.

Physical Model

The physical model is shown in Figure 48.

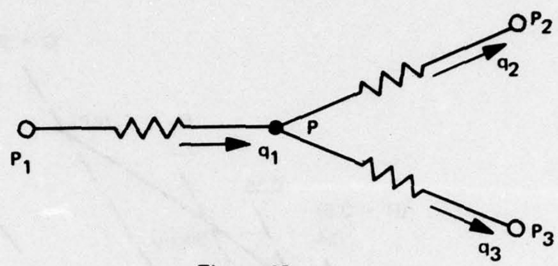


Figure 48

Mathematical Model

Let **P** denote the pressure at the branching point (Figure 48).

The flow-rate equations are:

$$P_1 - P = \Delta P_1, \quad G_1 = f_1(\Delta P_1), \quad q_1 = G_1\,\Delta P_1 \tag{79}$$

$$P - P_2 = \Delta P_2, \quad G_2 = f_2(\Delta P_2), \quad q_2 = G_2\,\Delta P_2 \tag{80}$$

$$P - P_3 = \Delta P_3, \quad G_3 = f_3(\Delta P_3), \quad q_3 = G_3\,\Delta P_3 \tag{81}$$

The continuity of flow-rate requires:

$$q_1 = q_2 + q_3 \tag{82}$$

Numerical values are: $P_1 = 80$, $P_2 = 10$, $P_3 = 20$ and the functional relationships given in Figure 47.

Computer Model, Method 1 (Diff. An., II.3-C)

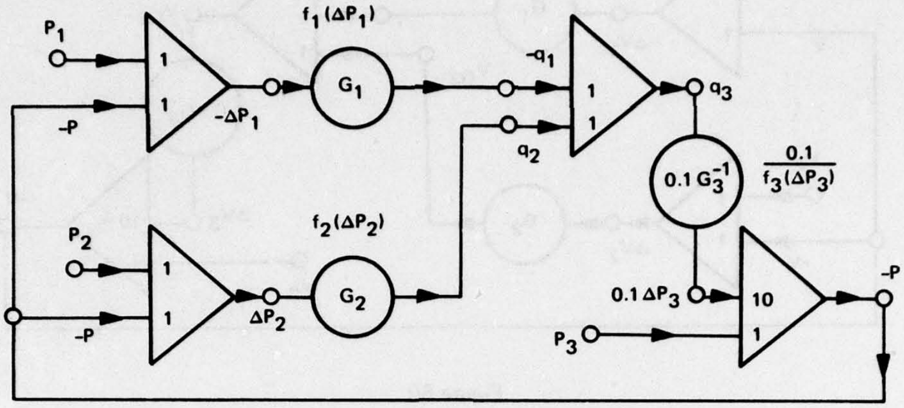


Figure 49

Since the magnitude of pressures P_1 and P_3 are above 10, scaling of pressures is required. Use 0.1 scale factor, i.e., (see Figure 49).

$$V_1 = 0.1(P_1) = 0.1(80) = 8 \text{ volts}$$

$$V_2 = 0.1(P_2) = 0.1(10) = 1 \text{ volt}$$

$$V_3 = 0.1(P_3) = 0.1(20) = 2 \text{ volts}$$

This scale factor will affect all values throughout the computer model (Figure 50). The relationships between voltages and the quantities they represent are

$$V_1 = 0.1(P_1) = 8 \text{ volts} \qquad V_{Q1} = 0.1\,q_1$$

$$V_2 = 0.1(P_2) = 1 \text{ volt} \qquad V_{Q2} = 0.1\,q_2$$

$$V_3 = 0.1(P_3) = 2 \text{ volts} \qquad V_{Q3} = 0.1\,q_3$$

$$\Delta V_1 = 0.1\,\Delta P_1, \quad \Delta V_2 = 0.1\,\Delta P_2, \quad \Delta V_3 = 0.01\,\Delta P_3$$

$$G_1 = f_1(\Delta P_1) = f_1(10\,\Delta V_1), \qquad G_2 = f_2(\Delta P_2) = f_2(10\,\Delta V_2),$$

$$G_3 = f_3(100\,\Delta V_3)$$

$$V = 0.1\,P$$

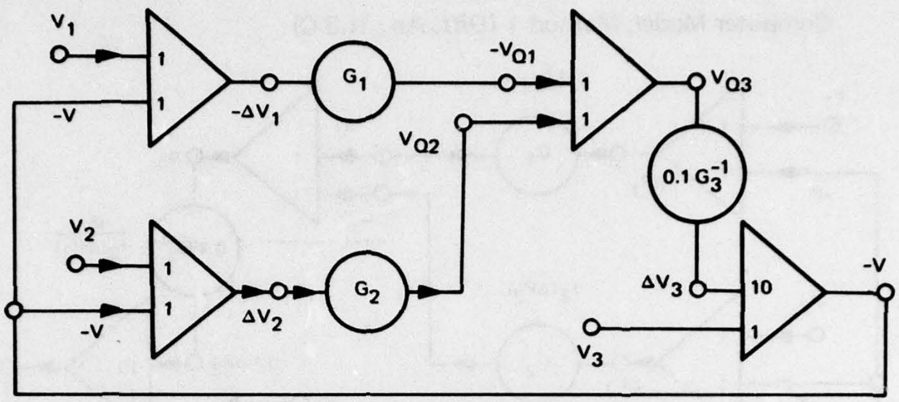


Figure 50

Discussion: Normalizing method of scaling
Effect of friction reducing agents
Automation

Computer Model, Method 2 (Passive Analogy—II.2-A)

Step 1—Scaling

Lable constant **G** lines in Figure 47 by corresponding **R** = 1/G values. From these values of **R**, it is concluded that $R_{max} \cong 15$.

Use the following conversion factors:

$$r = 1{,}000 \text{ ohm}/1 \text{ (psi sec/ft}^3) \quad (83)$$

$$v = 0.1 \text{ volt}/1 \text{ psi} \quad (84)$$

$$i = \frac{v}{r} = \frac{0.1}{1{,}000} \text{ amp/(ft}^3\text{/sec)} = 0.1 \text{ ma/(ft}^3\text{/sec)} \quad (85)$$

Step 2—Forming the model

Use initial guesses for pipeline resistances of sections 1, 2 and 3, use the above conversions and form the computer model of Figure 51.

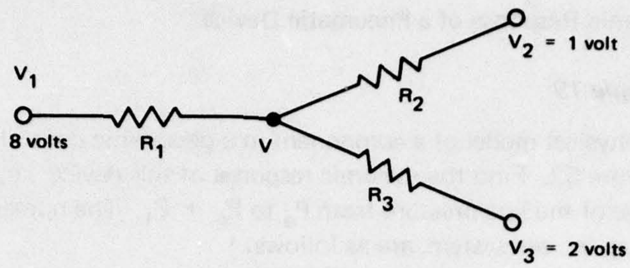


Figure 51

Step 3—Computer Run

a—Measure:

$$\Delta V_1 = V_1 - V$$

$$\Delta V_2 = V - V_2$$

$$\Delta V_3 = V - V_3$$

b—Compute:

$$\Delta P_1 = 10 \Delta V_1$$

$$\Delta P_2 = 10 \Delta V_2$$

$$\Delta P_3 = 10 \Delta V_3$$

c—Use Figure 51 and ΔP_1, ΔP_2, ΔP_3 to determine new values for R_1, R_2 and R_3.

d—Repeat a, b and c until R_1, R_2 and R_3 match values read from Figure 47 for ΔP_1, ΔP_2 and ΔP_3 (don't forget scale factors).

Discussion: Automation

B. Dynamic Response of a Pneumatic Device

Example 19

The physical model of a component in a pneumatic control system is shown in Figure 52. Find the dynamic response of this device, i.e., $\theta(t)$ for a sudden change of the line pressure from P_o to $P_o + P_1$. The numerical values, in lb, slug, in., sec system, are as follows:

$$A = 4. \quad , \; L = 2. \quad , \; d = 4 \quad , \; \rho_o = 1.375 \times 10^{-6}$$

$$(1/R) = 2 \times 10^{-6} \text{ (slug/sec)/(lb/in.}^2)$$

$K = 8$, $P_1 = 1.$, K is the stiffness of the bellows.

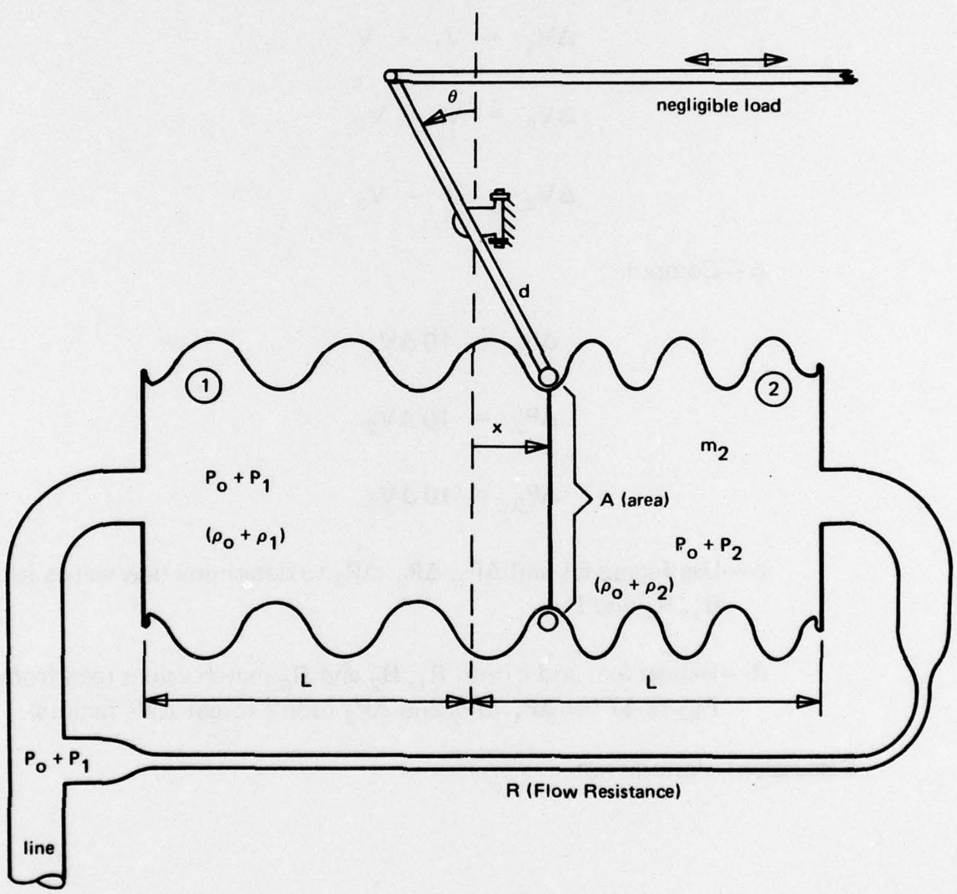


Figure 52

Mathematical Model

For small x:

$$\theta = \frac{x}{d} \tag{86}$$

$$(P_1 - P_2) A = K x \tag{87}$$

$$\dot{m}_2 = \frac{P_1 - P_2}{R} \tag{88}$$

Since $m_2 = A(L - x)(\rho_o + \rho_2)$

therefore
$$\dot{m}_2 \cong AL\dot{\rho}_2 - A\rho_o \dot{x} \tag{89}$$

From ideal gas law:

$$PV^{\gamma} = k, \quad \gamma = 1.4 \tag{90}$$

Since

$$\rho = \frac{1}{V} \tag{91}$$

therefore

$$P = k\rho^{1.4} \tag{92}$$

From the above expression:

$$P_o + P_2 = k(\rho_o + \rho_2)^{1.4} = k\rho_o^{1.4}\left(1 + \frac{\rho_2}{\rho_o}\right)^{1.4} \cong k\rho_o^{1.4}\left(1 + 1.4\,\frac{\rho_2}{\rho_o}\right) \tag{93}$$

or

$$P_2 = \left(\frac{1.4\,P_o}{\rho_o}\right)\rho_2 = K_a\rho_2, \quad K_a \triangleq 1.4\,P_o/\rho_o \tag{94}$$

For air, when P is in lb/in.^{2} and ρ in slug/in.^{3},

$$K_a \cong 1.5 \times 10^6 \text{ lb in./slug} \tag{95}$$

at sea level and T = 60°F.

Using Equation (94) in Equation (89), results in:

$$\dot{m}_2 = (AL/K_a)\dot{P}_2 - A\rho_o\dot{x} \tag{96}$$

and Equation (88) becomes

$$(AL/K_a)\dot{P}_2 - A\rho_o\dot{x} = \left(\frac{1}{R}\right)(P_1 - P_2) \tag{97}$$

or, when rearranged:

$$\dot{P}_2 = \frac{\rho_o K_a}{L}\dot{x} + \frac{1}{R}\,\frac{K_a}{AL}\,(P_1 - P_2) \tag{98}$$

Integration of both sides of the above expression results in

$$P_2 = \frac{\rho_o K_a}{L} x + \frac{K_a}{RAL}\int (P_1 - P_2)\,dt \tag{99}$$

Computer Model

The computer model is arranged by using Equations (86), (87) and (99), see Figure 53.

Numerical values are as follows:

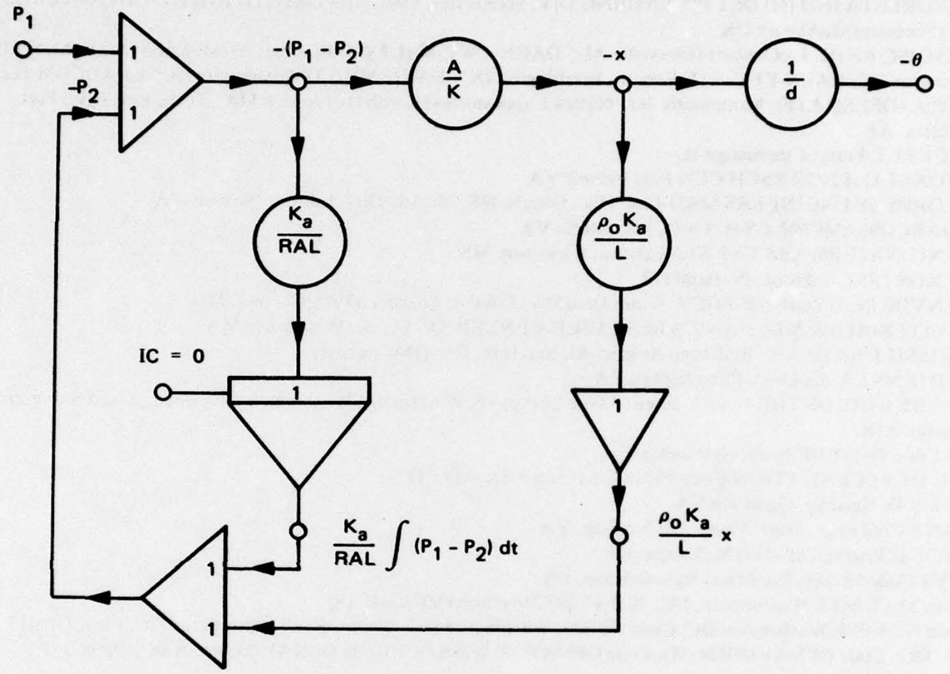
$$\frac{K_a}{RAL} = \frac{1.5 \times 10^6 \times 2 \times 10^{-6}}{4 \times 2} = 0.375$$

$$\frac{\rho_o K_a}{L} = \frac{1.375 \times 10^{-6} \times 1.5 \times 10^6}{2} = 1.03$$

$$\frac{A}{K} = \frac{4}{8} = 0.5$$

$$1/d = 0.25$$

A scale factor of 1 volt/1 psi may be used for converting P_1.



P1
-P2
1
1
-(P1 - P2)
A/K
-x
1/d
-θ
Ka/RAL
ρo Ka/L
IC = 0
1
1
Ka/RAL ∫ (P1 - P2) dt
ρo Ka/L x
1
1

Figure 53

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NAVOCEANSYSCEN Code 2010 San Diego, CA; Code 3400 San Diego CA; Code 409 (D. G. Moore), San Diego CA; Code 4473 Bayside Library, San Diego, CA; Code 52 (H. Talkington) San Diego CA; Code 5214 (H. Wheeler), San Diego CA; Code 5224 (R.Jones) San Diego CA; Code 6505 (J. Stachiw), San Diego, CA; Code 6565 (Tech. Lib.), San Diego CA; Code 6700, San Diego, CA; Code 7511 (PWO) San Diego, CA; Code 811 San Diego, CA; Research Lib., San Diego CA; SCE (Code 6600), San Diego CA
NAVORDSTA PWO, Louisville KY
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NAVPETRES Director, Washington DC
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NAVSEASYSCOM Code 0325, Program Mgr, Washington, DC; Code OOC (LT R. MacDougal), Washington DC; Code SEA OOC Washington, DC
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NAVSHIPREPFAC SCE Subic Bay
NAVSHIPYD; CO Marine Barracks, Norfolk, Portsmouth VA; Code 202.4, Long Beach CA; Code 202.5 (Library) Puget Sound, Bremerton WA; Code 380, (Woodroff) Norfolk, Portsmouth, VA; Code 400, Puget Sound; Code 400.03 Long Beach, CA; Code 404 (LT J. Riccio), Norfolk, Portsmouth VA; Code 410, Mare Is., Vallejo CA; Code 440 Portsmouth NH; Code 440, Norfolk; Code 440, Puget Sound, Bremerton WA; Code 440.4, Charleston SC; Code 450, Charleston SC; Code 453 (Util. Supr), Vallejo CA; L.D. Vivian; Library, Portsmouth NH; PWD (Code 400), Philadelphia PA; PWD (LT N.B. Hall), Long Beach CA; PWO, Mare Is.; PWO, Puget Sound; SCE, Pearl Harbor HI; Tech Library, Vallejo, CA
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